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Volume 4

Final Report

4

Architectural Options, Subsystems, Technology, and Programmatics

D180-27477-4

Space Station Needs, Attributes, and Architectural Options Study

(NASA-CR-173331) SPACE STATION NEEDS, ATTRIBUTES AND ARCHITECTURAL OPTIONS STUDY. VOLUME 4: ARCHITECTURAL OPTIONS, SUBSYSTEMS, TECHNOLOGY AND PROGRAMMATICS Final Report (Boeing Aerospace Co., Seattle, | N84-18268 | Unclas | G3/15 00686

Arthur D. Little, Inc. Battelle Life Systems, Inc. HAMILTON STANDARD RCA

ENVIRONMENTAL RESEARCH INSTITUTE OF MICHIGAN INTERMETRICS Microgravity Research Associates, Inc Econ

Space Station
Needs, Attributes and Architectural Options Study

Contract NASW-3680

D180-27477-4

Final Report

Volume 4

Architecture Options, Subsystems, Technology and Programmatics

April 21, 1983

for

National Aeronautics and Space Administration

Headquarters

Washington, D. C.

Approved by

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BOEING

FOREWORD

The Space Station Needs, Attributes and Architectural Options Study (Contract NASW-3680) was initiated in August of 1982 and completed in April of 1983. This was one of eight parallel studies conducted by aerospace contractors for NASA Headquarters. The Contracting Officer's Representative and Study Technical Manager was Brian Pritchard. The Boeing study manager was Gordon R. Woodcock.

The study was conducted by Boeing Aerospace Company and its team of subcontractors:

Arthur D. Little, Inc. (ADL)	Materials Processing in Space
Battelle Columbus Laboratories	Materials Processing in Space
ECON, Inc.	Pricing Policies and Economic Benefits
Environmental Research Institute of Michigan (ERIM)	Earth Observation Missions
Hamilton Standard	Environmental Control and Life Support Equipment
Intermetrics, Inc.	Software
Life Systems, Inc. (LSI)	Environmental Control and Life Support Equipment
Microgravity Research Associates (MRA)	Materials Processing in Space
National Behavioral Systems (NBS)	Crew Accommodations and Architectural Influences
RCA Astro-Electronics	Communications Spacecraft
Science Applications, Inc. (SAI)	Space Science

This document is one of seven final report documents:

D180-27477-1	Volume 1, Executive Summary
D180-27477-2	Volume 2, Mission Analysis
D180-27477-3	Volume 3, Requirements
D180-27477-4	Volume 4, Architectural Options, Subsystems, Technology, and Programmatics
D180-27477-5-1	Volume 5-1, National Defense Missions and Space Station Architectural Options Final Report (SECRET)
D180-27477-5-2	Volume 5-2, National Defense Missions and Space Station Architectural Options, Final Briefing (SECRET)
D180-27477-6	Volume 6, Final Briefing

D180-27477-7-1	Volume 7-1, Science and Applications Missions Data Book
D130-27477-7-2	Volume 7-2, Commerical Missions Data Book
D180-27477-7-3	Volume 7-3, Technology Demonstration Missions Data Book
D180-27477-7-4	Volume 7-4, Architectural Options, Technology, and Programmatics Data Book
D180-27477-7-5	Volume 7-5, Mission Analysis Data Book

Note: The volume 7 data books will be distributed to a limited number of requestors.

The study task descriptions and a final report typical cross reference guide are found in Appendix 1.

The Boeing and subcontractor team member are listed in Appendix 2.

Acronyms and abbreviations are listed in Appendix 3.

PREFACE

Volume 4 includes reports on 1) space station architectural options, 2) habitability considerations and subsystem analyses, 3) technology and 4) programmatics.

The architectural options section presents the methodology employed for conceiving and defining space station concepts. As a result of this approach, architectures were conceived and along with their supporting rationale are described within this portion of the report.

Habitability consideration and subsystem analyses describe the human factors associated with space station operations and includes subsections covering 1) data management, 2) communications and tracking, 3) environmental control and life support, 4) manipulator systems, 5) resupply, 6) pointing, 7) thermal management and 8) interface standardization.

The technology section of this report presents a consolidated matrix of subsystems technology issues as related to meeting the mission needs for a 1990's era space station.

Within the programmatics portion, a brief description of costing and program strategies is outlined.

VOLUME 4

SECTION I
ARCHITECTURAL OPTIONS

1.0 ARCHITECTURAL OPTIONS

Through knowledge we behold the world's creation,
How in his cradle first he fostered was;
And judge of Nature's cunning operation,
How things she formed of a formless mass . . . .

From thence we mount aloft into the sky,
And look unto the crystal firmament,
There we behold the heaven's great hierarchy,
The stars' pure light, the spheres' swift movement. . . .

EDMUND SPENSER
The Tears of the Muses

1.1 INTRODUCTION

The purpose of this section is to report not only the resultant space station architectures but to describe the process shaping their design. The documentation of this process affords accountability in tracing decisions from concept to configuration and intentionally stresses an analytical approach to space station design.

The approach is inclusive and considers the merits of all approaches toward workable space station architecture. It maintains an optimistic yet realistic attitude and considers an evolutionary cost conscious posture relative to capabilities and growth. Furthermore, it is accommodating, in that a user-friendly policy was a part of the analysis, (see fig. 4.1-1) and that the envisioned architecture allows tolerance with respect to the evolving mission model. In other words, a single space station architecture is not so closely tailored to one mission model that it can't accommodate variations of that model.

1.1.1 Section Organization

Methodology - is a brief outline of the process used in identifying and integrating the design issues leading to space station architectures.

Space Station Architecture Options - describes the features and attributes of resultant space station schemes.

Summary - is a digest of space station architecture findings.

- **Technical**
  - **Low contamination; environment control flexibility**
  - **Adequate services**
    - **Power**
    - **Thermal control**
    - **Ports and workspace**
    - **Data, computation, languages**
- **Operational**
  - **Frequent access**
  - **Visiting scientists**
- **Institutional**
  - **Minimum bureacracy**
  - **Turnkey capability for those who need it**
  - **Short time scales – get on, get results, get off**
  - **User charge structure**
  - **Proprietary protection**

Figure 4.1.1 User Friendly Approach

1.1.2 Terminology

For the purpose of maintaining consistency and clarity within this report, the following terms and definitions will be used.

Architecture - is the distribution of space station functions and their relative positioning. Basically, the schemes depict zoning strategies and operational relationships.

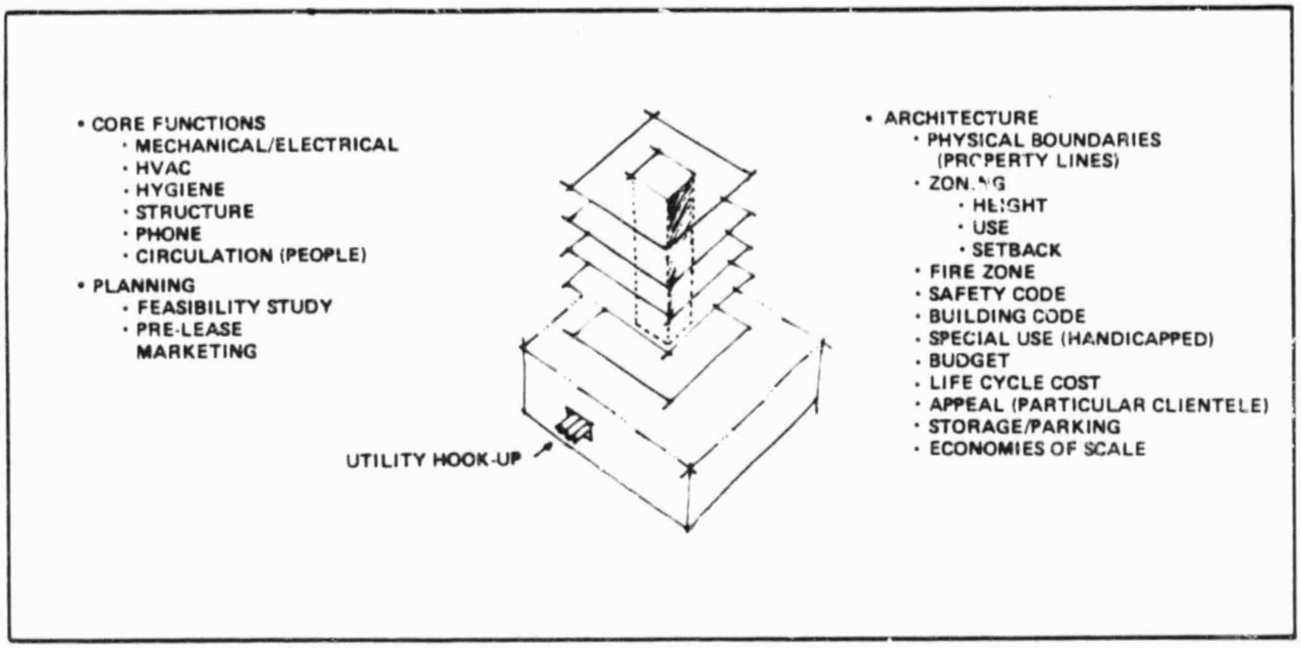
Configuration - is a further development of architecture, incorporating dimensions, rough order of magnitude weights, delivery packaging and other conceptual design issues necessary to test the architectural level idea for feasibility.

Layout - refers to the internal arrangement of the space station or individual module and overlaps configuration in the allocation and selection of subsystems.

ORIGINAL PAGE IS OF POOR QUALITY

1.1.3 Analogy

The process of developing a space station architecture bares a marked similarity to the planning and design of an office building, as illustrated in figure 4.1-2. In each case, the sensible approach begins with a feasibility study. This involves 1) an analysis of the demand, 2) an



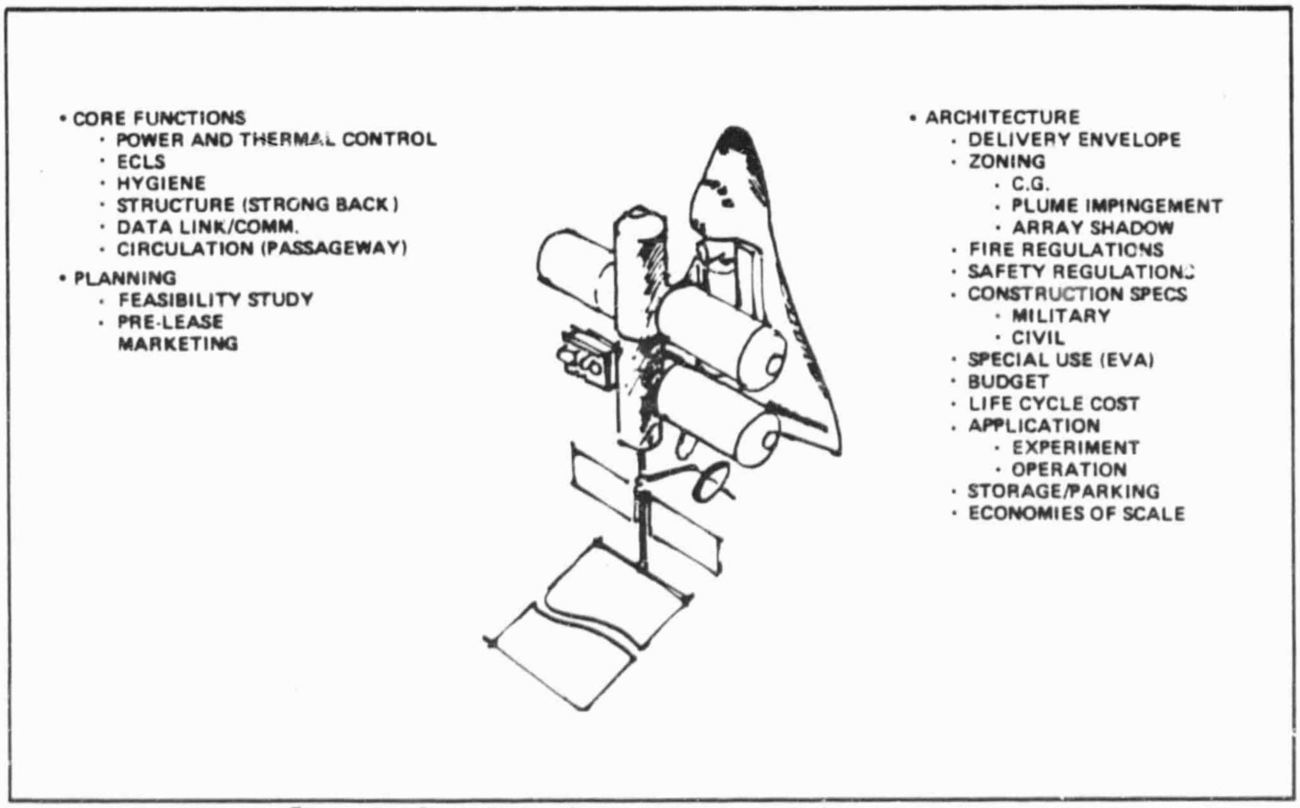


Figure 4.1-2 Office Building Analog to a Space Station

examination of the means for satisfying this demand and 3) an understanding of the cost/benefits associated with the venture. By no means is this a formula-like process, in fact, success may very well depend upon the inventive and creative strategies for implementation.

Provided the feasibility study findings are positive, financing plans need to be determined. This may include an active marketing campaign as well as encouraging pre-lease arrangements.

Both office building and space station architectures must provide similar core functions. These include, 1) mechanical and electrical support, 2) environmental control, 3) structural integrity, 4) communications infrastructure, 5) personal hygiene provisions, 6) effective user traffic patterns (for normal and emergency conditions) and 7) adaptable accommodations.
The comparison continues into the conceptual design level where each architecture must realize:

1. physical boundaries (property lines or shuttle payload bay)
2. zoning (use, set-back, height or center of gravity thruster plume impingement, array shadowing, etc.)
3. fire codes
4. safety codes
5. building codes
6. budget
7. life-cycle cost
8. energy conservation
9. appeal - what features will attract the anticipated users
10. storage - permanent and transient
11. economics of scale
12. number of copies

In addition to serving as a useful model for explaining the space station architecture, the office building analog provided the rationale for anticipating common user requirements. By so doing, we were able to conceptualize architectural relationships early-on, allowing the mission models to later define, size or modify the product of this advanced thinking.

When science from Creation's face
Enchantment's veil withdraws,
What lovely visions yield their place
To cold material laws!

THOMAS CAMPBELL

1.2 METHODOLOGY

Open/Limited

We began with a very broad approach to architectural investigations to ensure that opportunities were not overlooked. We investigated an open class, in which "anything goes," and a limited class, tied to a conventional premise.

The basic distinction between the open and limited classes of space station thinking is that the open class accepts ideas of opportunity whereas the limited class traces the implications of a premise through a network of logical consequences. (See fig. 4.1-3 & 4.1-4)

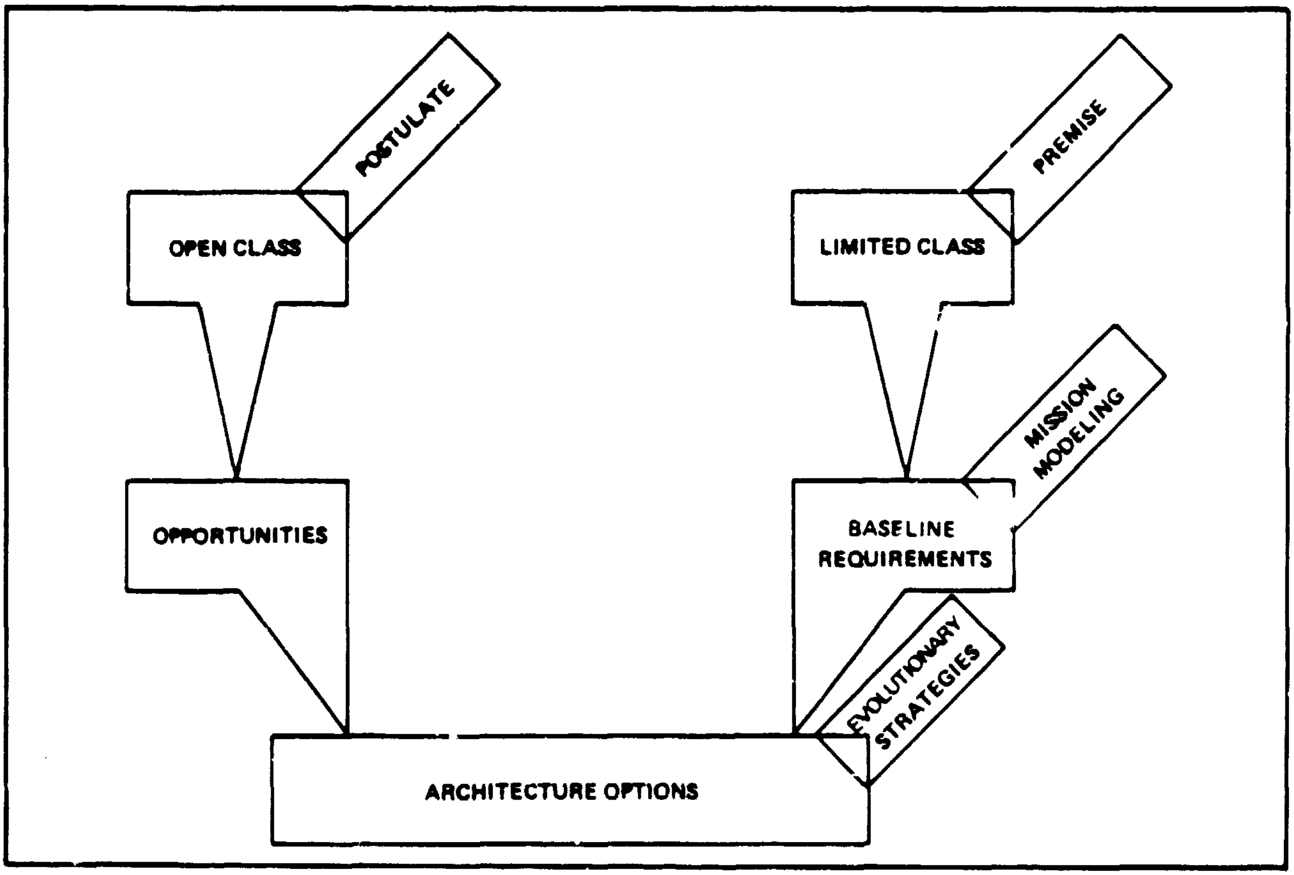


Figure 4.1-3 Methodology Leading to Architectural Options

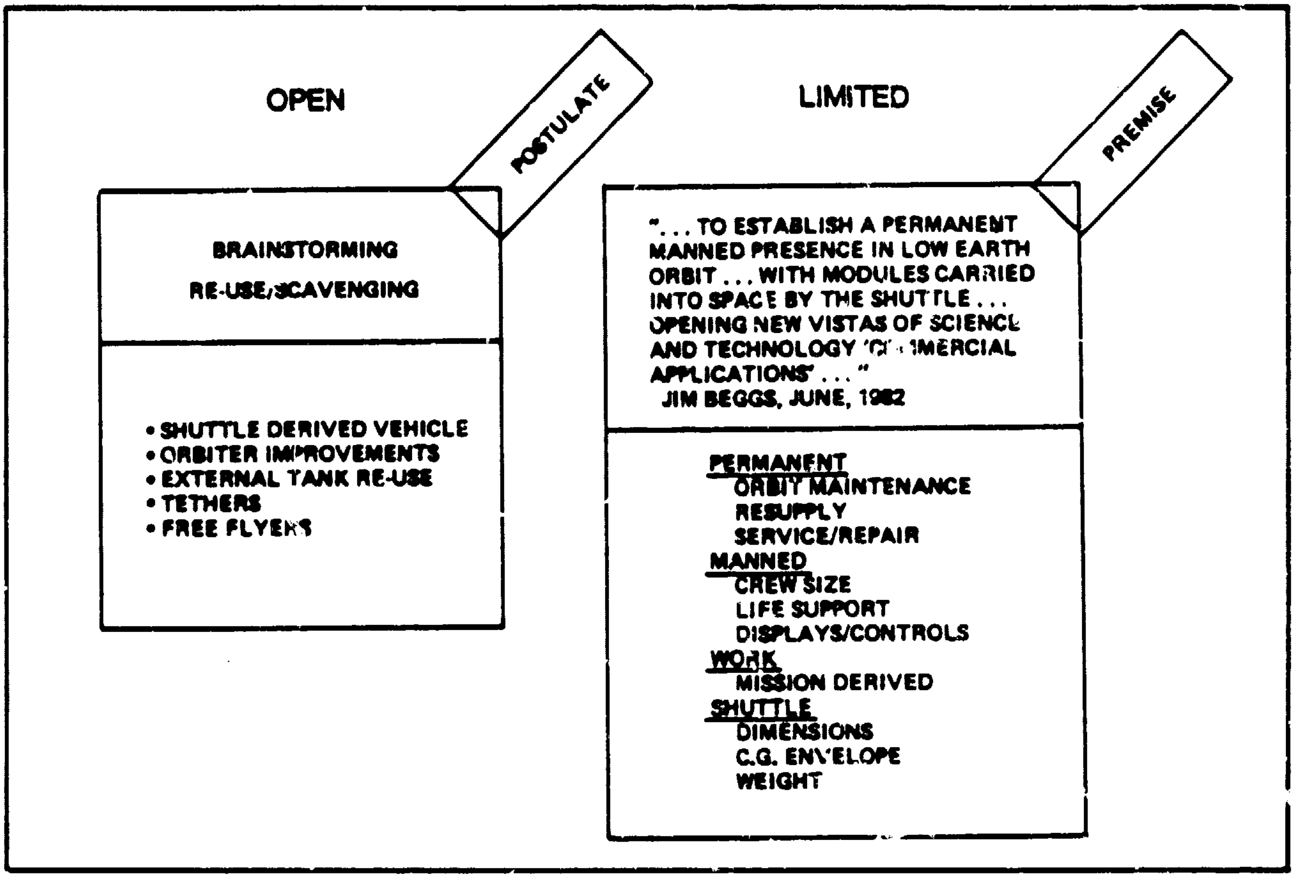


Figure 4.1-4 Distinctions Between Open and Limited Classes

1.2.1 Open Class

The open class is postulate based. That is, any scheme proposed will be accepted for consideration. It is a category intended to stimulate brainstorming and ideas which occur in an unstructured situation. Within the open class, we have explored space staion concepts which incorporate re-use and scavenging as techniques to take advantage of existing hardware. In particular, the shuttle external tank was seen as a prime opportunity. Additional concepts utilizing tethers, free flyers and shuttle derived launch vehicles were considered. The following descriptions briefly outline the findings of the preliminary analysis of candidate open class schemes.

1.2.1.1 Shuttle External Tank

This 27 foot diameter pressure vessel can reach orbit with every shuttle launch. It appears at first glance to be a space station in waiting. On closer examination. this opportunity proves less attractive, as evidenced by the following discussion:

STS design - as testimony to sensible engineering, the only discardable component of the shuttle system is virtually worthless after performing its duty. The valuable, reusable elements, such as motors, pumps, etc., are located on the reclaimed portions of the STS. In essence, the external tank has been carefully designed to be thrown away. The structure and insulation are intended to perform service from launch pad to orbit and are not meant to survive permanent residence on-orbit. Certainly, the shuttle external tank (E.T.) can be modified for space station occupancy, but not without considering the following issues:

Safety - despite the large available volume - two means of egress from a pressure vessel are required for any manned station. This suggests additional modules in order to meet the requirement. Therefore, considering the two means of egress requirement, volume is not necessarily an asset.

Control - as configured, the E.T. does not possess requisite control characteristics for space station operations. It is possible to achieve adequate control authority by providing a reaction control/reboost system coupled with navigation and guidance support. However, owing to the inherent moments of inertia, atmospheric drag and orientation requirements the control demands are significant. Initial calculations reveal that an inertially oriented E.T. station that included an aft cargo compartment habitat would require 100,000 ft-lbs-sec or 20 Skylab sized control moment gyros for sufficient control capability. (See fig. 4.1-5 & 4.1-6)

Contamination - without attention to the insulation characteristics under prolonged exposure in a vacuum, ultra violet radiation and material outgassing encouraged by heat of the ride to orbit, the desired "clean" space station environment may be unobtainable or seriously degraded. Furthermore, adequate thermal protection must be supplied for a habitable environment. This is not a part of the external tank and would need to be considered as a necessary alteration prior to occupancy.

Growth - the evolutionary growth of an E.T. based space station is principally configuration dependent. However, on the architectural level, growth can occur either as an addition of other E.T. modules or of some shuttle payload sized modules. The former provides very large growth increments while the latter represents a mixed system not taking advantage of commonality for standarization and cost reduction.

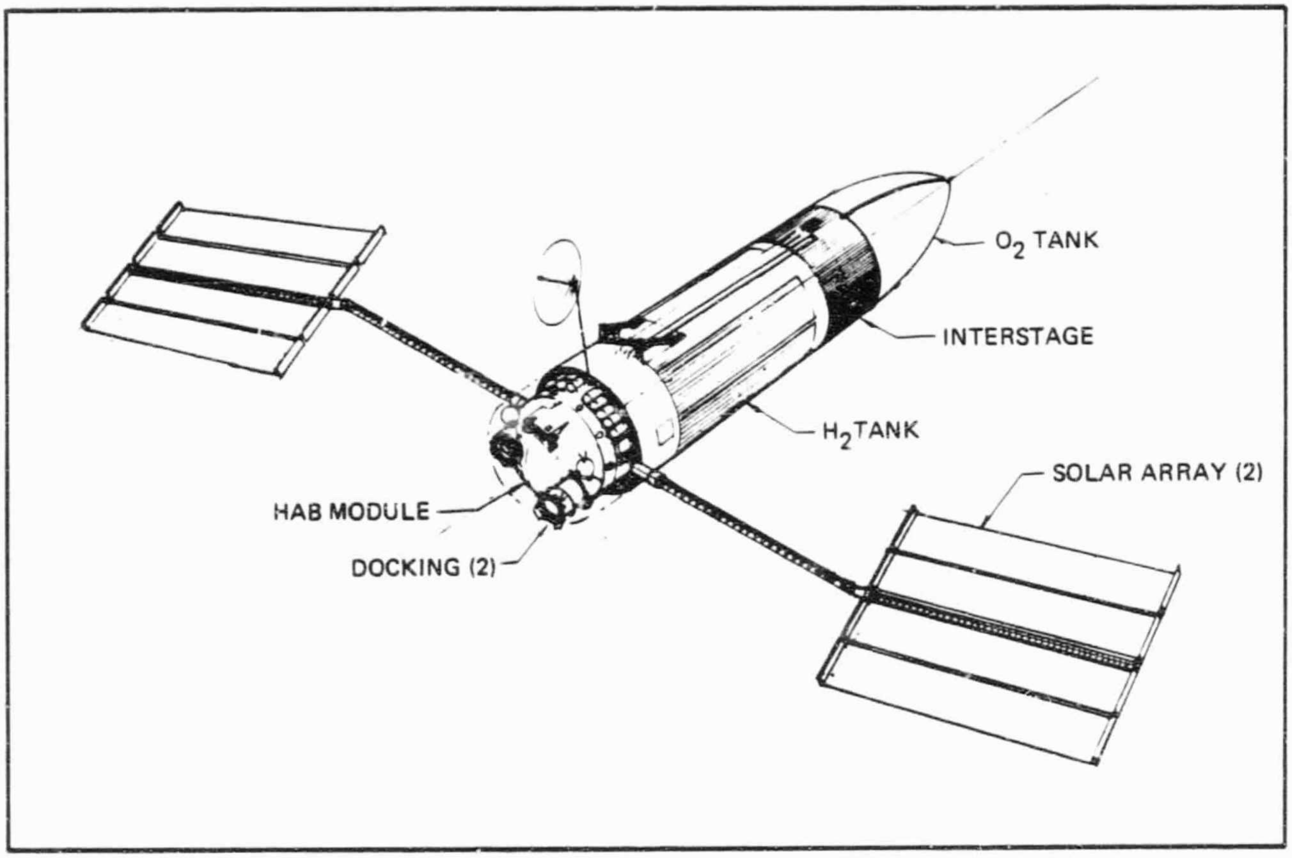


Figure 4.1-5 External Tank Space Station

Return - a space station sized to the shuttle payload bay has the opportunity of being returned to the earth. Obviously, an E.T. station would not. Therefore, reliability, maintainability, and adaptability requirements of the E.T. station become essential design characteristics, which translates into higher cost.

Aft Cargo Compartment (A.C.C.) - the opportunity of using the proposed A.C.C. must consider the temperature and accoustics environment of this location during launch and the penalty of the structure required to provide this capability. Presently, Martin Marietta calculates approximately 16,600 lbs for a general purpose A.C.C., reducing the overall STS payload by 7400 lbs from the eastern test range (ETR).

Debris Protection - a space station is required to have debris (meteoroid) protection. Based on the current debris model (1978), a standoff aluminum shield in conjunction with the pressure vessel wall provides the most efficient protection (See fig. 4.1-7). An E.T. derived station would need to have acceptable debris protection. With the efficient standoff type arrangement, penalties in additional design, manufacturing and a reduced payload would easily render the E.T. station, unacceptable.

INDEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS, M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
1	1	1.1.1	ET STATION	49219 (108520	18.4 60.3	0.0 0.0	0.0 0.0)	SUM
2	2	1.1.1.1	ET H2 TANK	13109 (28900	22.4 73.5	0.0 0.0	0.0 0.0)	MARTIN DATA
3	2	1.1.1.2	ET INTERTANK	5480 (12090	40.7 133.5	0. 0.	0.0 0.0)	MARTIN DATA
4	2	1.1.1.3	ET LOX TANK	5602 (12350	52.1 170.9	0.0 0.0	0.0 0.0)	MARTIN DATA
5	2	1.1.1.4	ACC STATION	22000	3.0	0.0	0.0	ROUGH ORDER OF MAGNITUDE ESTIMATE
6	2	1.1.1.5	POWER SYSTEM	3020 (6657	3.8 12.5	0.0 0.0	0.0 0.0)	SUM
7	3	1.1.1.5.1	25 KW S/A #1	1260 (2777	3.8 12.5	2.5 8.2	0.0 0.0)	SOC DATA
8	3	1.1.1.5.2	S/A MAST #1	250 (551	3.0 12.5	6.5 21.3	0.0 0.0)	SOC DATA
9	3	1.1.1.5.3	25 KW S/A #2	1260 (2777	3.0 12.5	-2.5 -8.2	0.0 0.0)	SOC DATA
10	3	1.1.1.5.4	S/A MAST #2	250 (551	3.8 12.5	-6.5 -21.3	0.0 0.0)	SOC DATA

MASS STATEMENT FOR

ET SPACE STATION

INDEX	IN-DENT	WBS & TITLE	MASS	SHAPE & ORIENT	IXX	IYY	IZZ
1	1	1.1.1 ET STATION	49219 108500	COMPOSITE SHAPE 0.00 0.00 0.00	784213. 18600992.	16165553. 383600400.	16311709. 387070592.
2	2	1.1.1.1 ET H2 TANK	13109 28900	CYLINDER SHELL 1.00 0.00 0.00	220362. 5229087.	1067313. 25326804.	1067313. 25326804.
3	2	1.1.1.2 ET INTERTANK	5480 12090	CYLINDER SHELL 1.00 0.00 0.00	92253. 2189124.	67900. 1611240.	67900. 1611240.
4	2	1.1.1.3 ET LOX TANK	5602 12350	CYLINDER SHELL 1.00 0.00 0.00	89632. 2126923.	168849. 4006701.	168849. 4006701.
5	2	1.1.1.4 ACC STATION	22000 48501	SOLID CYLINDER 1.00 0.00 0.00	184910. 4387822.	198340. 4706707.	198340. 4706707.
6	2	1.1.1.5 POWER SYSTEM	3020 6657	COMPOSITE SHAPE 0.00 0.00 0.00	197056. 4676037.	28931. 686514.	175167. 4156610.
7	3	1.1.1.5.1 25 KW S/A #1	1260 2777	RECTANGULAR PLATE 1.00 0.00 0.00	78330. 1858732.	12705. 301483.	65625. 1557240.
8	3	1.1.1.5.2 S/A MAST #1	250 551	ROD 0.00 1.00 0.00	3521. 83540.	0. 0.	3521. 83540.
9	3	1.1.1.5.3 25 KW S/A #2	1260 2777	RECTANGULAR PLATE 1.00 0.00 0.00	78330. 1858732.	12705. 301483.	65625. 1557240.
10	3	1.1.1.5.4 S/A MAST #2	250 551	ROD 0.00 -1.00 0.00	0. 0.	3521. 83540.	3521. 83540.

MOMENTS OF INERTIA FOR

ET SPACE STATION CONCEPT

Figure 4.1-6 Mass and Moments of Inertia for External Tank Space Station

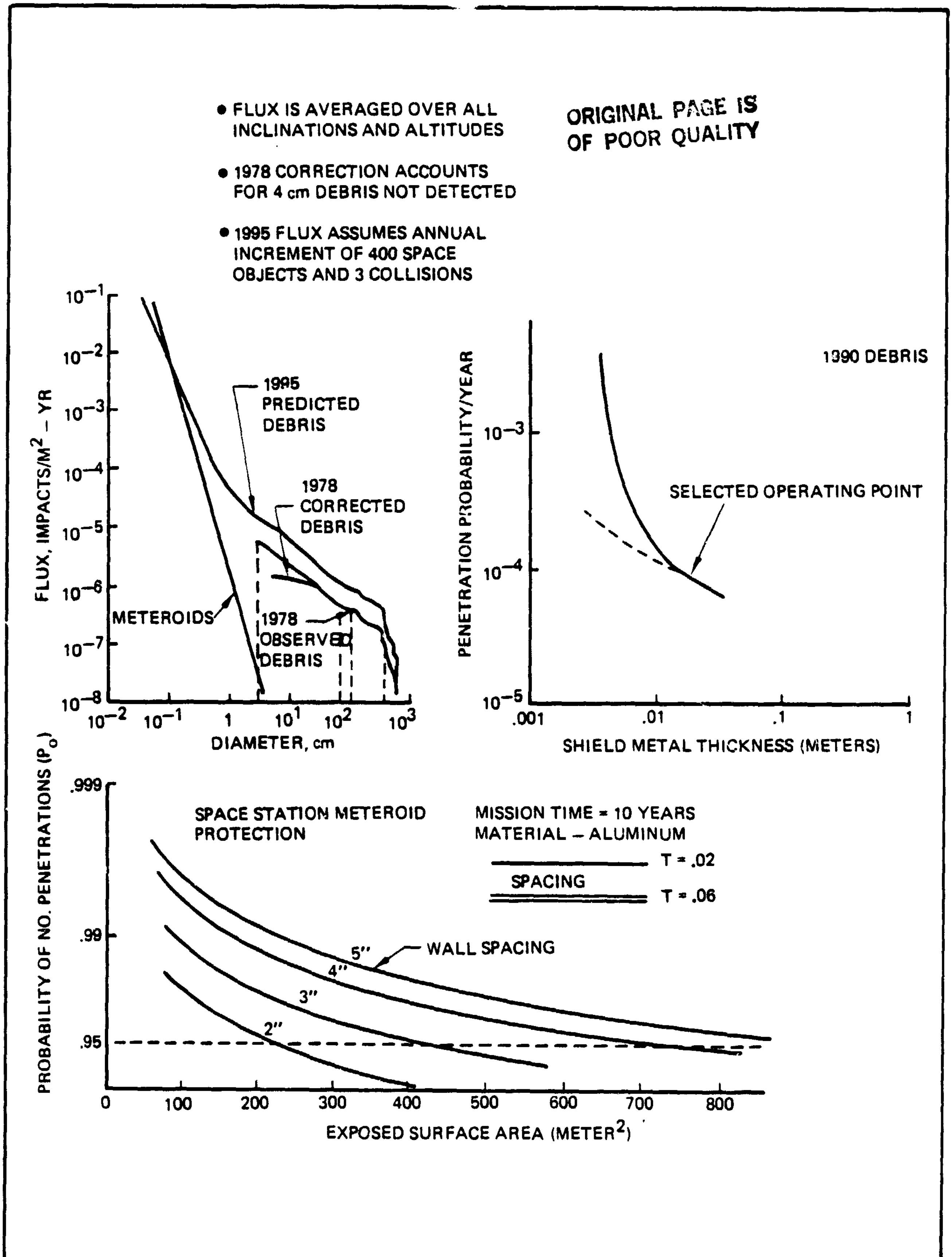


Figure 4.1-7 Debris Protection for LEO Space Station

In conclusion, an external tank space station would demand extensive modification to meet manned space station requirements. Depending on configuration, these modifications could outweigh any benefits accrued from its use.

1.2.1.2 Tethers

As part of open class thinking, we explored tethered space station architectures (see fig. 4.1-8). First the potential applications of tethered arrangements were examined, then the associated cost/benefits were investigated. The identified applications include, controlled microgravity environments, power generation, independent orientations and orbit transfer assistance. For the purpose of this analysis, the tether was envisioned as a permanent, integral architectural element. Otherwise, it is possible, as with the orbiter, to accommodate tethered payloads on a case by case basis.

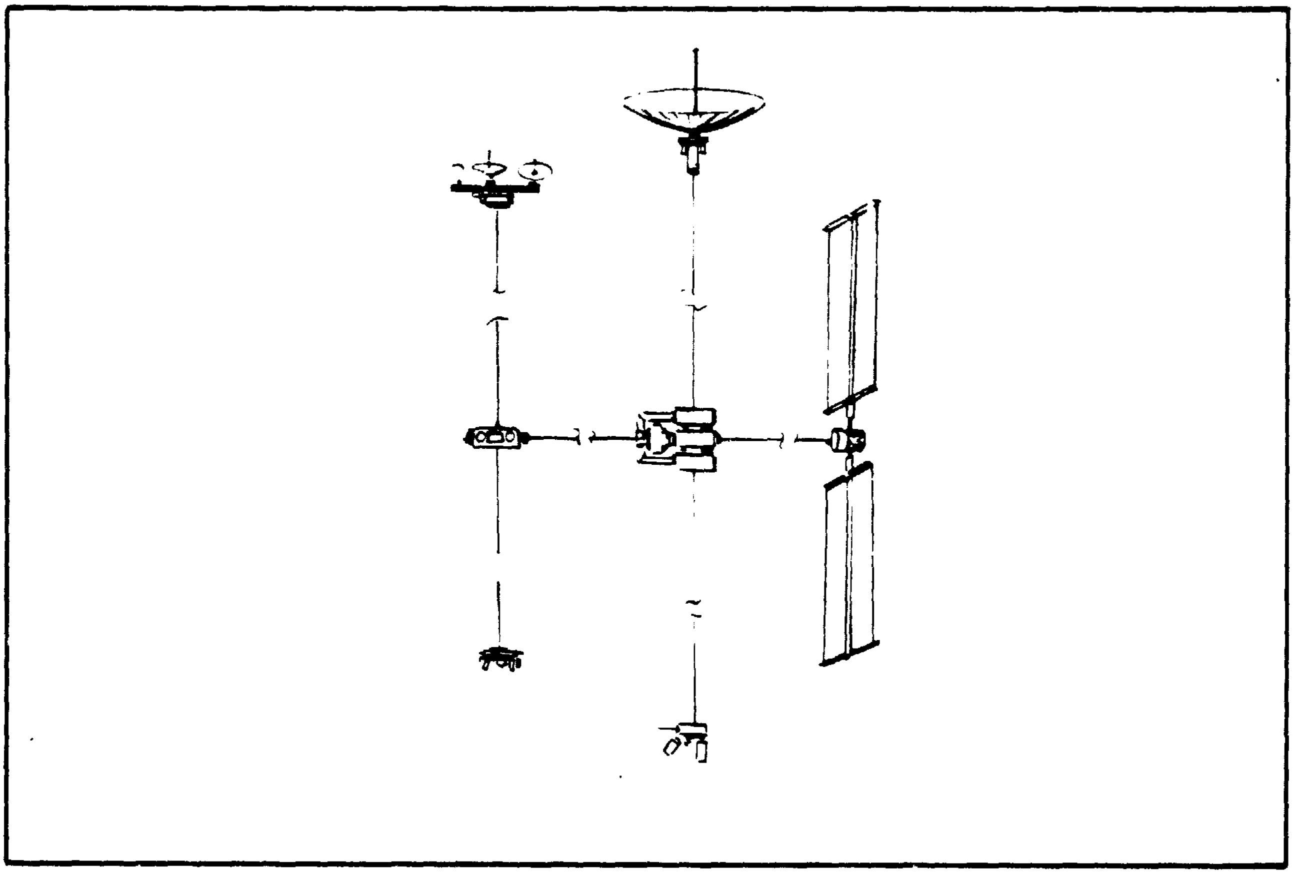


Figure 4.1-8 Tethered Space Station

Controlled Micro-gravity

Tethered arrangements inherently produce micro-gravity conditions which vary according to the mass balance and length of tether. This can be used as a means of on-orbit fluid transfer, as well

as providing a directional reference for space station functions.

Tethered architectures used in this manner were not aggressively pursued since, 1) they represented a risk without significant offsetting advantage, 2) control in the event of instability imposed considerable contingency penalties, 3) fluid transfer can be achieved by other, more conventional, means (internal bladder for fluids and temperature/pressure differential for cryogenics) and 4) station build-up with STS interface either created large mass imbalances or operational difficulties (handling payloads under micro-gravity conditions).

Power Generation

The tethered scheme as power generator relies on the gravity gradient stabilized assembly using the earth's magnetic field and plasma field to naturally produce electricity. The power levels created under these conditions are not enough to adopt a tethered arrangement on this feature alone.

Independent Orientations

By tethering scientific or power platforms both station and tether can, to a degree, assume independent orientations. As a scientific option which can provide an environment or orientation unavailable on the station we remain open, however do not see sufficient justification to drive a space station to this overall architecture. As a power platform, the array orientation control, servicing resupply, transmission losses through the tether, and redundancy all represent substantial barriers to acceptance.

Orbit Transfer Assistance

The characteristics of the tether arrangement allow imparting angular velocity to payloads for orbit transfer. This sudden mass imbalance will present control problems as well as produce a potentially dangerous loose tether situation. Therefore, with respect to the tether as a launch platform, the marginal advantage does not appear to overcome the identified risk, to make this architecture attractive.

1.2.1.3 Free Flyers

The consideration of free flying space platforms can be reduced to the necessary dependence between space station and satellite (see fig. 4.1-9). The co-existence of unmanned platforms is

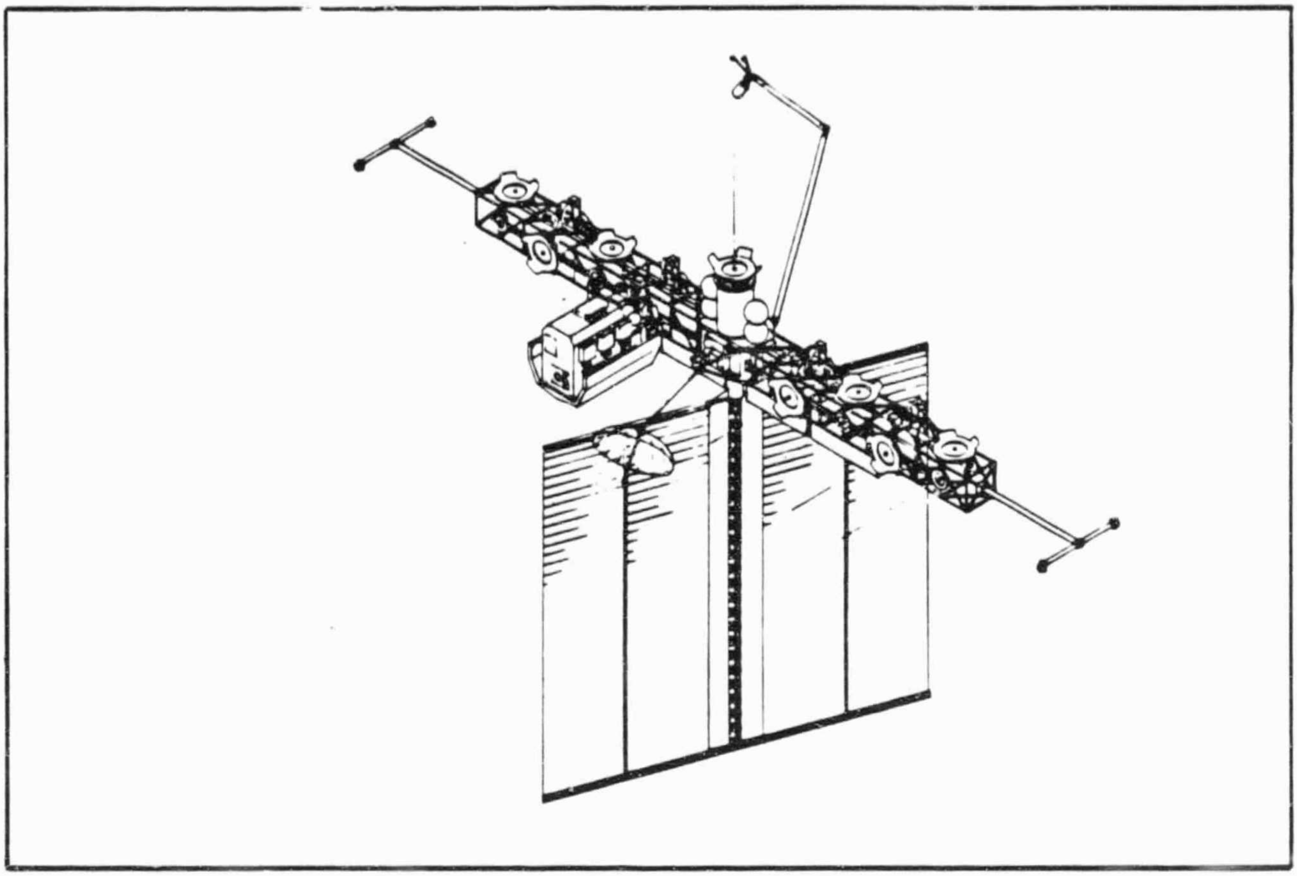


Figure 4.1-9 Free Flyer Associated with a Space Station

seen an inevitable. However, the issue is, to what extent is the space station affected because of the free flyers. The association may require crew time and hardware to monitor free flyer status and service its operations. Maintaining tight formation flight may jeopardize the reason for having a free flyer (microgravity, environment, reduced contamination, etc.). Therefore, the RF link to free flyers may need to rely on other than line of sight communications. This means that space station-free flyer communications may be direct but also may use satellite or ground relays for continual coverage.

The servicing of the free flyers can be either from the shuttle or space station. The station offers a low energy response to scheduled or unscheduled supply/return, maintenance and repair. Considering this situation, the space station would need either to automate the routine exchange and provide an unmanned vehicle with its support equipment or devise a means of manned servicing. In either case, this capability is envisioned as being necessary for other station operations therefore, frequency of service and storage accommodations would be the only unique free flyer requirements imposed on a space station.

1.2.1.4 Shuttle Derived Launch Vehicle

Alternate configurations of STS hardware provide some very encouraging opportunities (see fig. 4.1-10). These arangements of new and existing equipment realize a heavy-lift potential. Since it demonstrates a departure from a modest start-up, the shuttle derived launch vehicle was not considered for the initial space station. It should be noted that, owing to limits of growths and the envisioned commercial demand, a second generation station might well benefit from a shuttle derived launch vehicle.

1.2.1.5 Spacelab Hardware

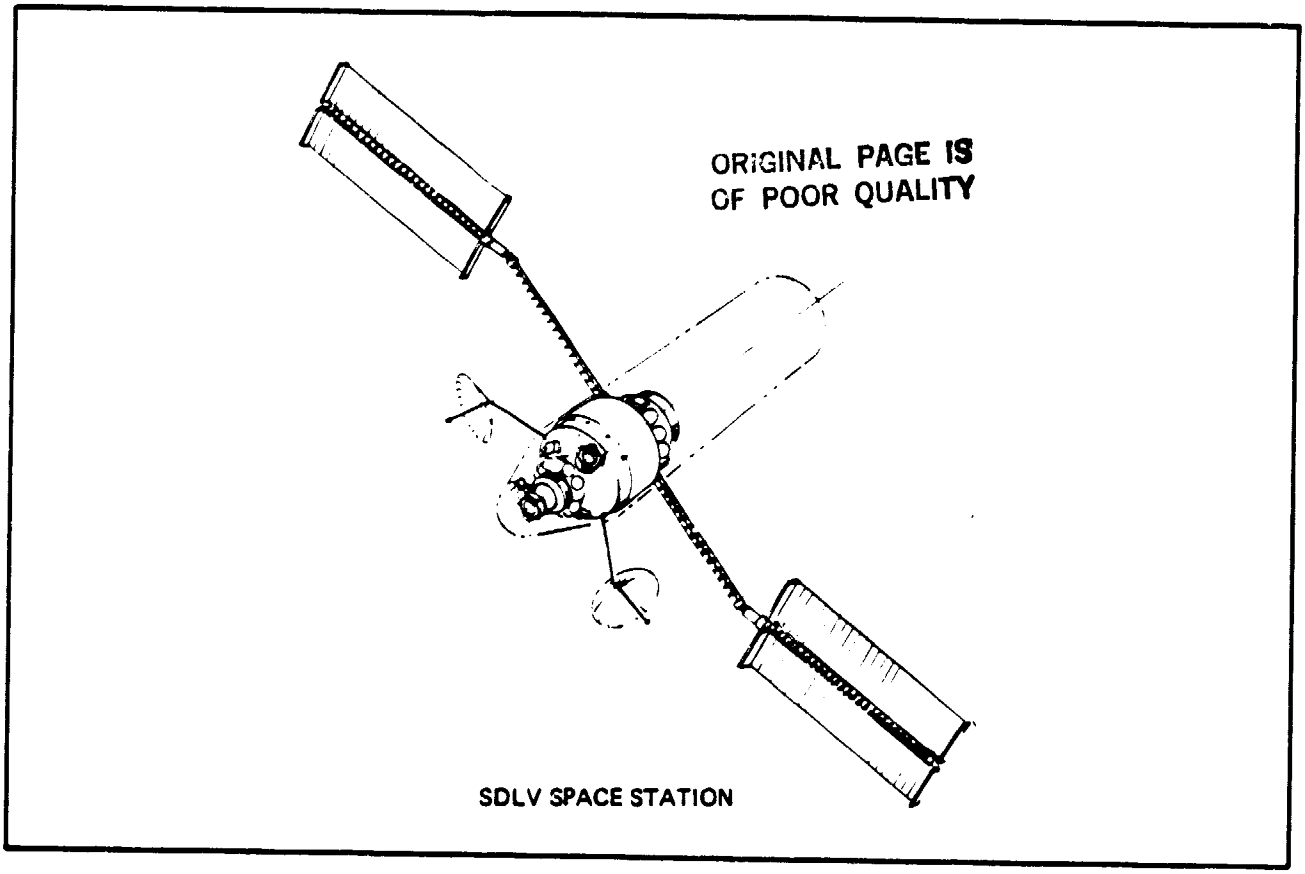
The use of Spacelab hardware as part of a 1990's era space station must take into account that:

1. The last pressurized module has been delivered and the production line was to be closed within the 4-6 weeks following its delivery.
2. The power distribution and mechanical ground support equipment were shut down earlier.
3. The remaining production lines are to be shut down by mid 1983.
4. And a NASA/ESA memo of understanding states that ESA will retain production capability. This is interpreted to mean the production line will be disassembled, however, tooling will be retained and NASA would presumably have to bear startup costs.

1.2.2 Limited Class

The limited class of space station thinking is not so much limited as directed. Guidance is supplied by a premise which embodies the objectives of this study effort and reads:

> "I believe that our next logical step is to establish a <u>permanent manned</u> presence in low-earth orbit. This can be done by developing a manne space station. At NASA we have begun to focus on that goal. W .hink that such a station could be built and placed in orbit by 1990. It would be small at first, assembled in orbit with modules carried to space by the <u>shuttle</u>. Once there, the station would make a vital contribution to our nation's future, by opening new vistas of <u>science and technology</u>, new possibilities for <u>commercial applications</u>



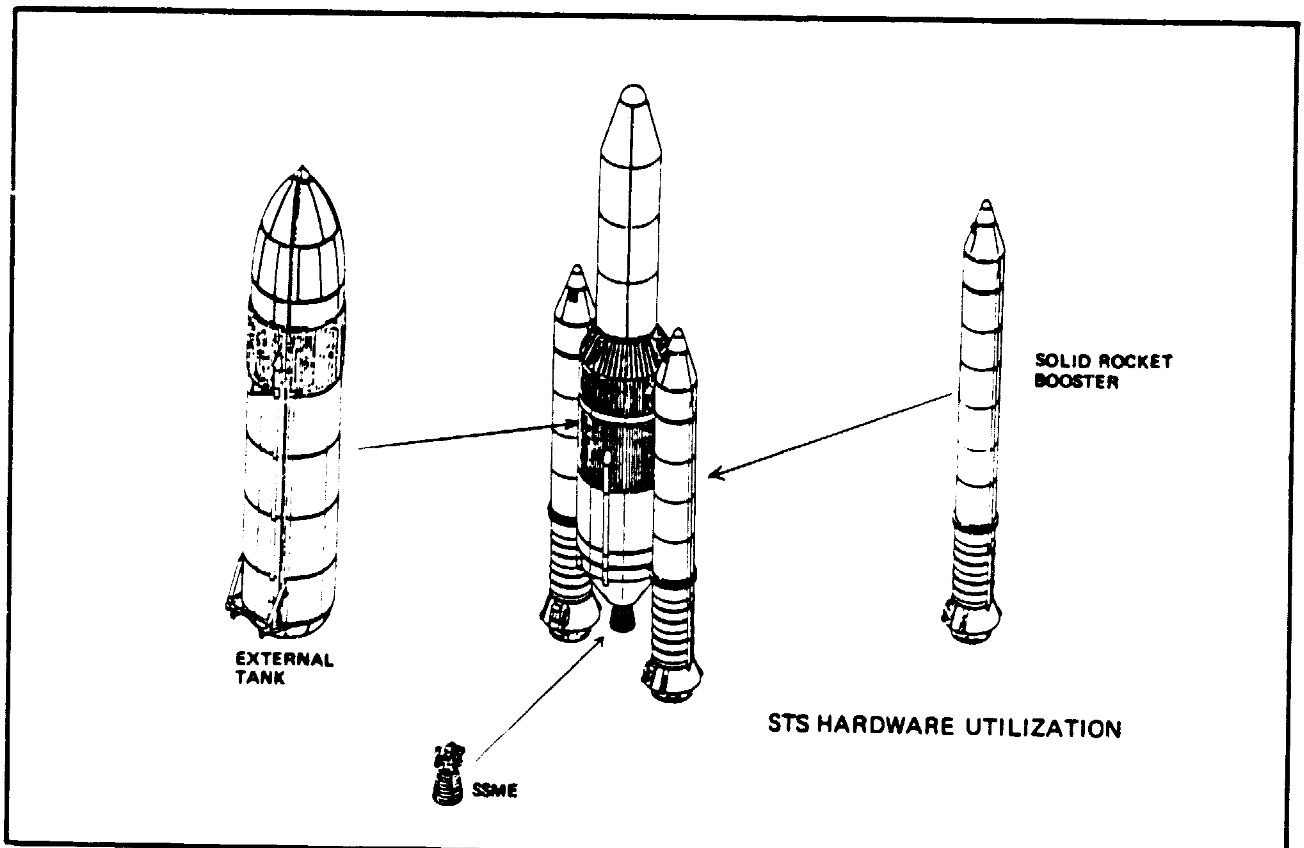


Figure 4.1-10 Shuttle Derived Launch Vehicle and a Potential Application

of space, and new opportunities to enhance economic security and the national defense.

Jim Beggs, June 23, 1982
—From a speech to the Detroit Economic Club

Each of the underlined words represent the tip of a logic pyramid necessary to provide that capability. By tracing the implications of these terms a rational and accountable means of developing space station architectures is recorded.

1.2.2.1 Permanent

Much of the permanence of a space station is simply remaining in orbit. Therefore, the space station must possess sufficient capability to maintain its orbit. To satisfy this requirement, the initial orbit selection should not only accommodate the mission demands for orbit selection, but include shuttle performance, atmospheric drag and resupply as a function of altitudes and inclination. An example of how the mission analysis relates to the control authority of a permanent space station is displayed in figure 4.1-11.

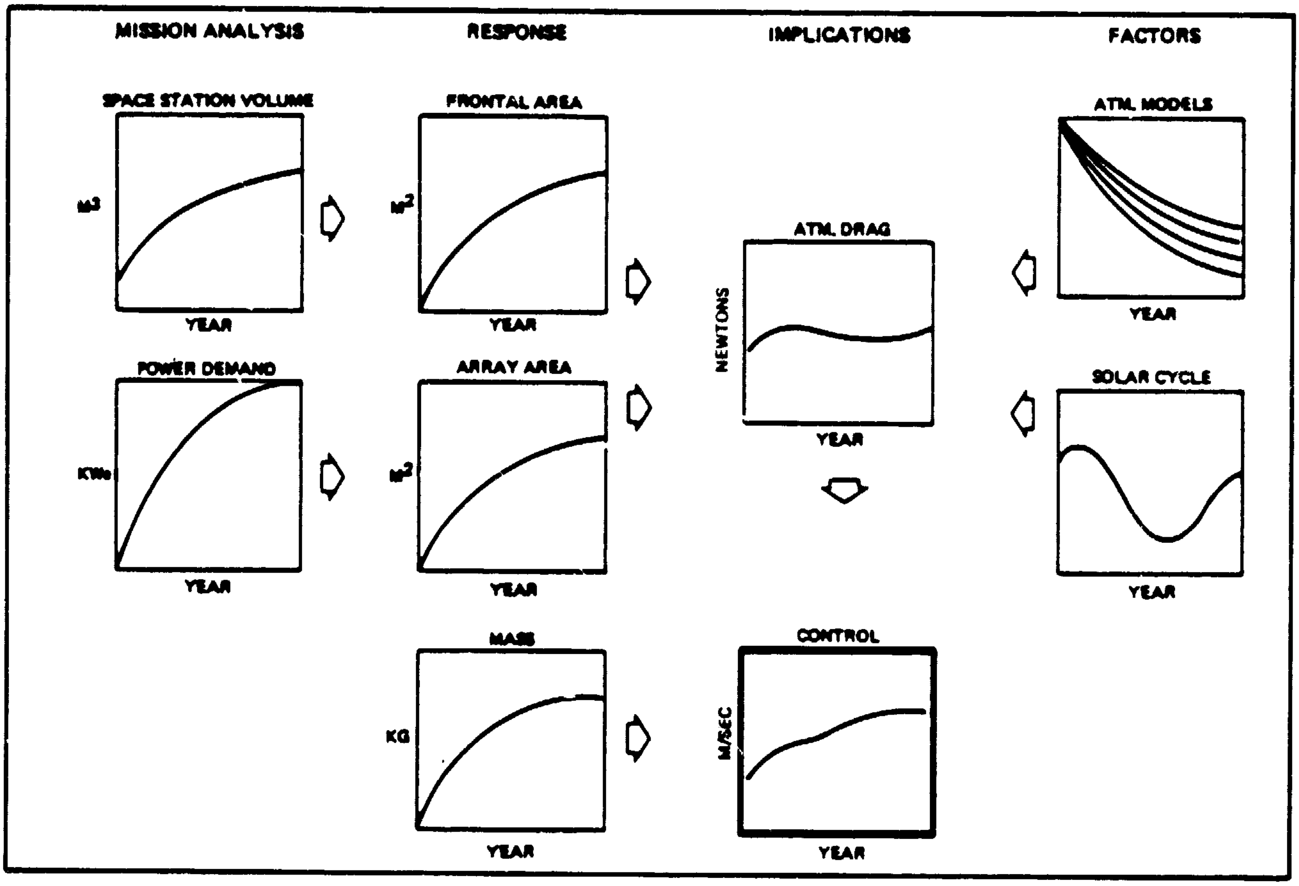


Figure 4.1-11 Factors Influencing a Permanent Space Station

Since a prudent, cost sensitive approach to space station design provides a basis of technology selection, not all systems will be autonomous or closed. Therefore, resupply of consumables and crew becomes an essential feature to a permanent space station. The issue of resupply establishes the logical connection to how much of what by when. This, in turn, can be analyzed for both the scheduled resupply of sustenance items (food, gases, propellant, etc.) and mission requirements (materials processing, scientific equipment, etc.). In addition, provisional accommodations for unscheduled resupply should be factored-in to satisfy contingency measures.

Permanence also connotes a continuance of operation. Any manned space station will be a highly integrated system of hardware and software and place demands on reliability and maintainability. Therefore, maintenance, servicing and repair will be part of this system and should be seen as one of the principal design drivers.

1.2.2.2 Manned

The "manned" attribute initiates a whole chain of implications. First and foremost, a life support system is required. Once identified, the type and interfaces needs to be traded against cost, capability, growth, reliability, resupply, etc. Also, life support for extra vehicular activity (EVA) crewmembers must be considered. This represents another interface in capabilities (atmosphere type, pressure), contamination, and requisite life support.

Crew size, skills, training, duty time, accommodations, etc., are part of the many integrated issues woven into a manned space station. These can be more clearly defined by analysis of both mission and station requirements/capabilities. The creation of mission models provides a reasonable point of departure for establishing initial and subsequent growth capabilities. This, in turn, establishes a rationale for space station crew sizing and accommodations. Fig. 4.1-12 follows the mass and volume accommodations for a manned space operation.

Another concern of the manned station is control authority. The crew should have varying degrees of influence over the station's operation. This requires the availability of reliable information so the appropriate action can be taken. The trade in this area involves the degree of expert system or autonomy and its corresponding cost, technology development and reliability.

1.2.2.4 Science and Technology...Commercial Applications (WORK)

Work, with respect to the space station, represents mission operations. This involves the environment (atmosphere, radiation, gravity, etc.) orientation, the utility interface (power, data,

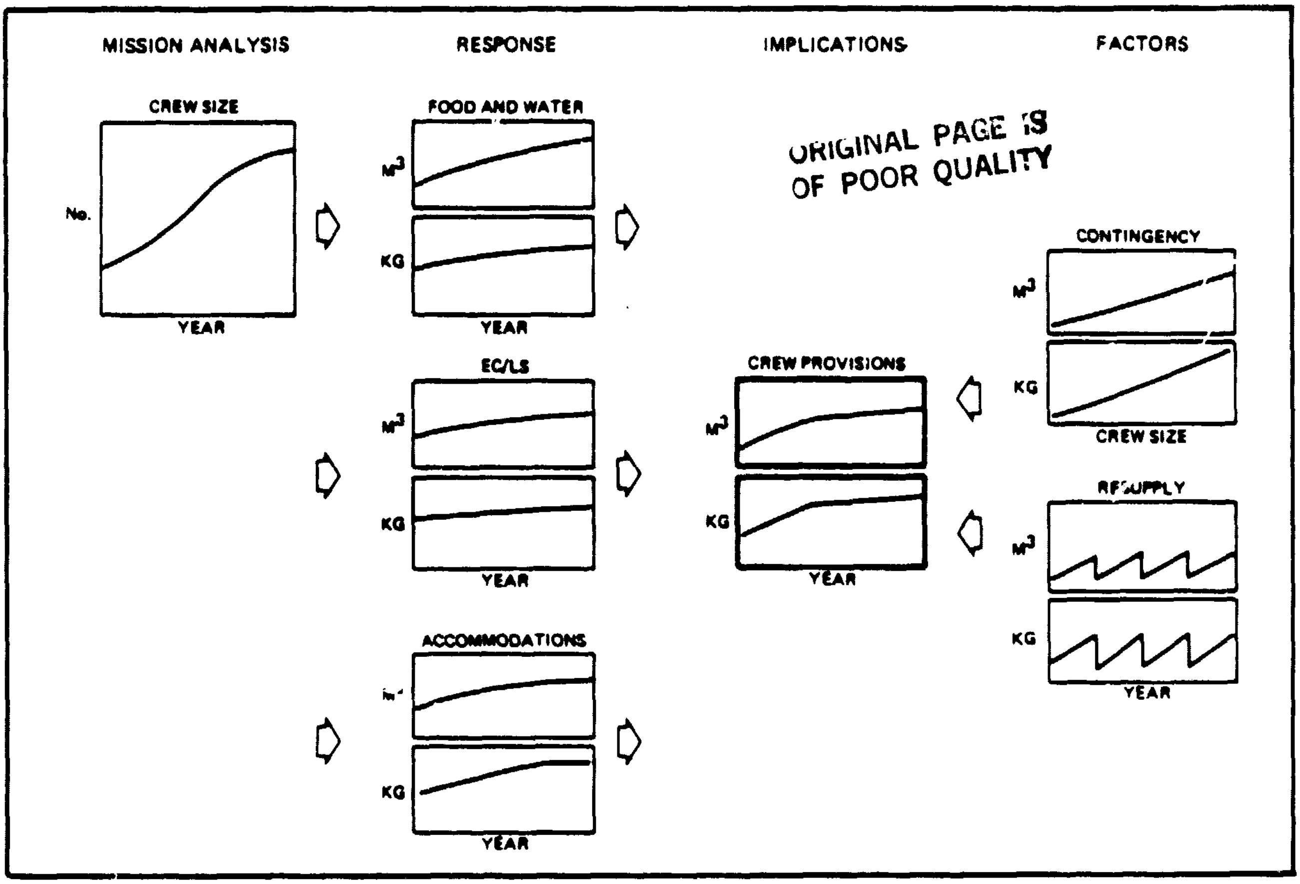


Figure 4.1-12 Factors Influencing a Manned Space Station

thermal control, etc.), structural conditions, crew time and other features desired to carry out scientific and commercial missions. Our mission analysis has produced time phased user demand models which can be converted to space station mass, volume and power required to support various models, as symbolized by figure 4.1-13.

The findings of our mission analysis, as interpreted for space station architecture, are summarized below:

Orbit Inclination - there is sufficient demand for a space station at both a high (polar) and low (28.5^{o}) inclination orbits. However, there appears to be no justification to warrant a space station at the median (55^{o}) inclination orbits. Few missions have been identified and those can best be served by a free-flyer.

Missions for Orbit Inclinations - high inclination orbits would provide support for earth observation missions with some satellite servicing. Low inclination missions would accommodate micro-gravity processing, astro and solar physics, life sciences, technology demonstrations, propellant storage, earth observations and satellite servicing.

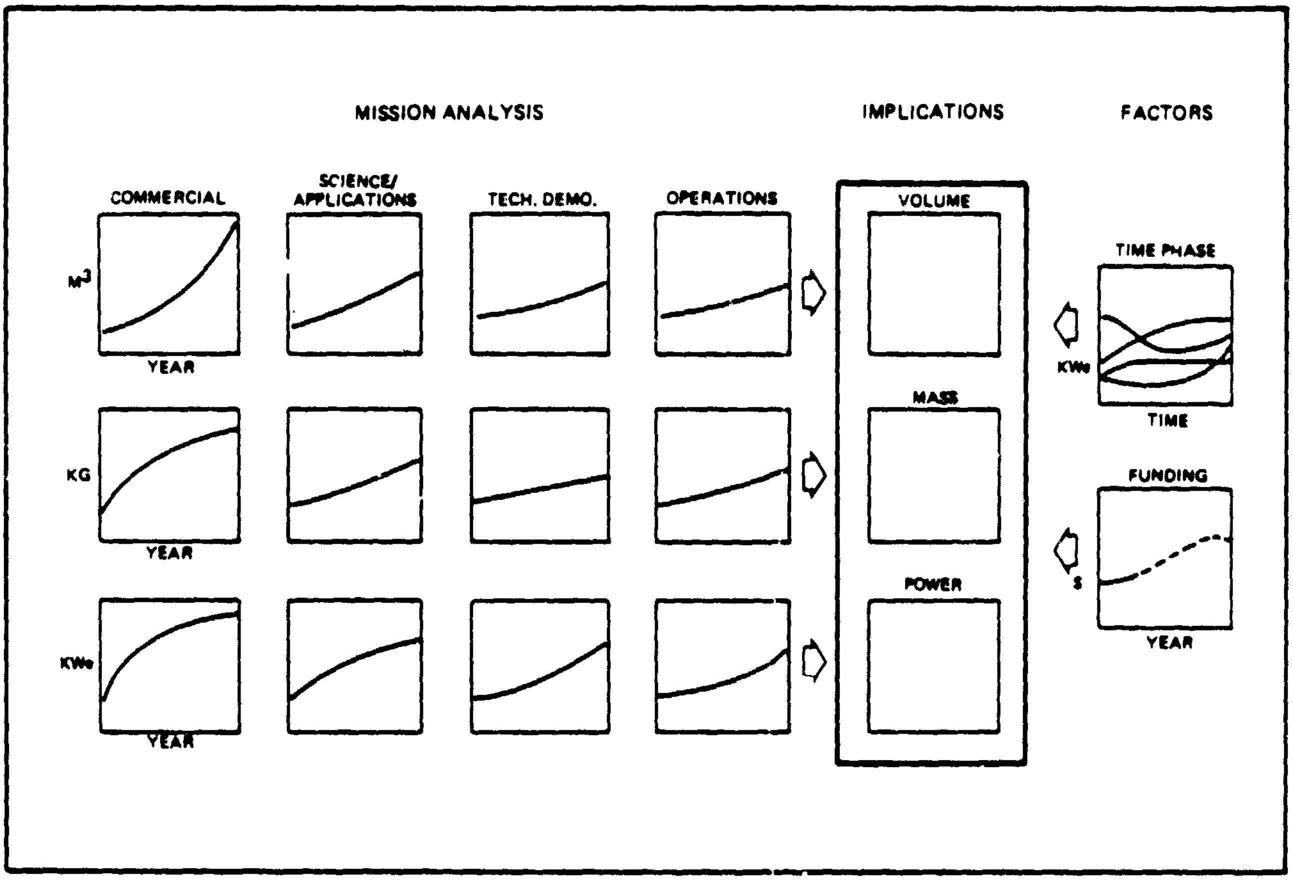


Figure 4.1-13 Mission Accommodation Factors Influencing a Space Station

Mission modeling reveals that the crew required in support of the high inclination orbit begins at three and grows by only one crewmember, being sustained into the next century by a crew of four. The low inclination space station follows a different model beginning with a crew of 6 and eventually grows to 13 or more which then gives rise to another station to satisfy increased demand.

Further analysis indicates that the electrical power required for support of high inclination missions starts at 15 KW and increases to approximately 45 KW in 1997. The power projection for the low inclination space station is 25 KW during the first year to over 100 KW beginning in 1997.

1.2.2.3 Shuttle

A shuttle-delivered and serviced space station creates the situation of having to organize activities and capabilities into a sensible sequence of packaged elements (see fig. 4.1-14). In doing this, each package must fit within the dimensional (docking module attached) and

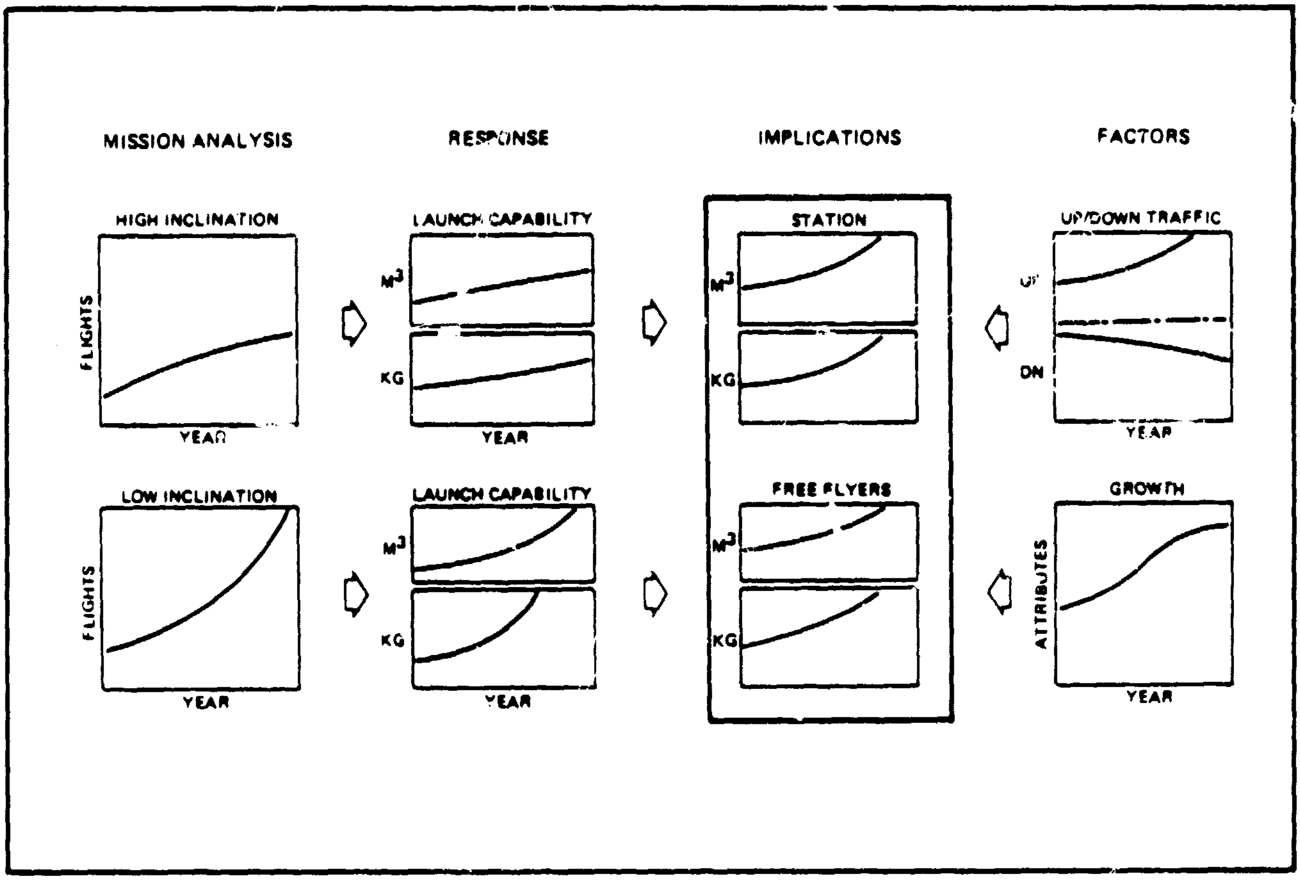


Figure 4.1-14 The Shuttle's Influence on a Space Station

performance (mass & c.g.) envelope of the STS (see fig. 4.1-15). Many factors contributed to a 500 KM altitude for the low inclination architecture and figure 4.1-16 shows the shuttle direct insertion capability and orbit decay rates for that altitude. In addition, the assembly and servicing of the station must realize the implications of a shuttle interface. This means providing docking ports in locations that respect the orbital mechanics of rendezvous and docking, as well as, clearance (with tolerance for misalignment), payload handling, control in the docked configuration and thruster plume impingements. Station build-up will take advantage of existing and proposed payload handling aids such as the remote manipulator system (RMS), payload installation deployment apparatus (PIDA) and handling and positioning aid (HPA).

Furthermore, the lift capability between low and high inclination orbits is significantly different. Therefore, any modular commonality between the two inclination architectures must recognize the maximum launch weight of 32,000 lb (14,515 kg) to polar orbit and 65,000 lb (29,484 kg) to a low inclination orbit. Obviously, the distribution of activities among modules requires careful planning for sensible space station buildup in either orbit.

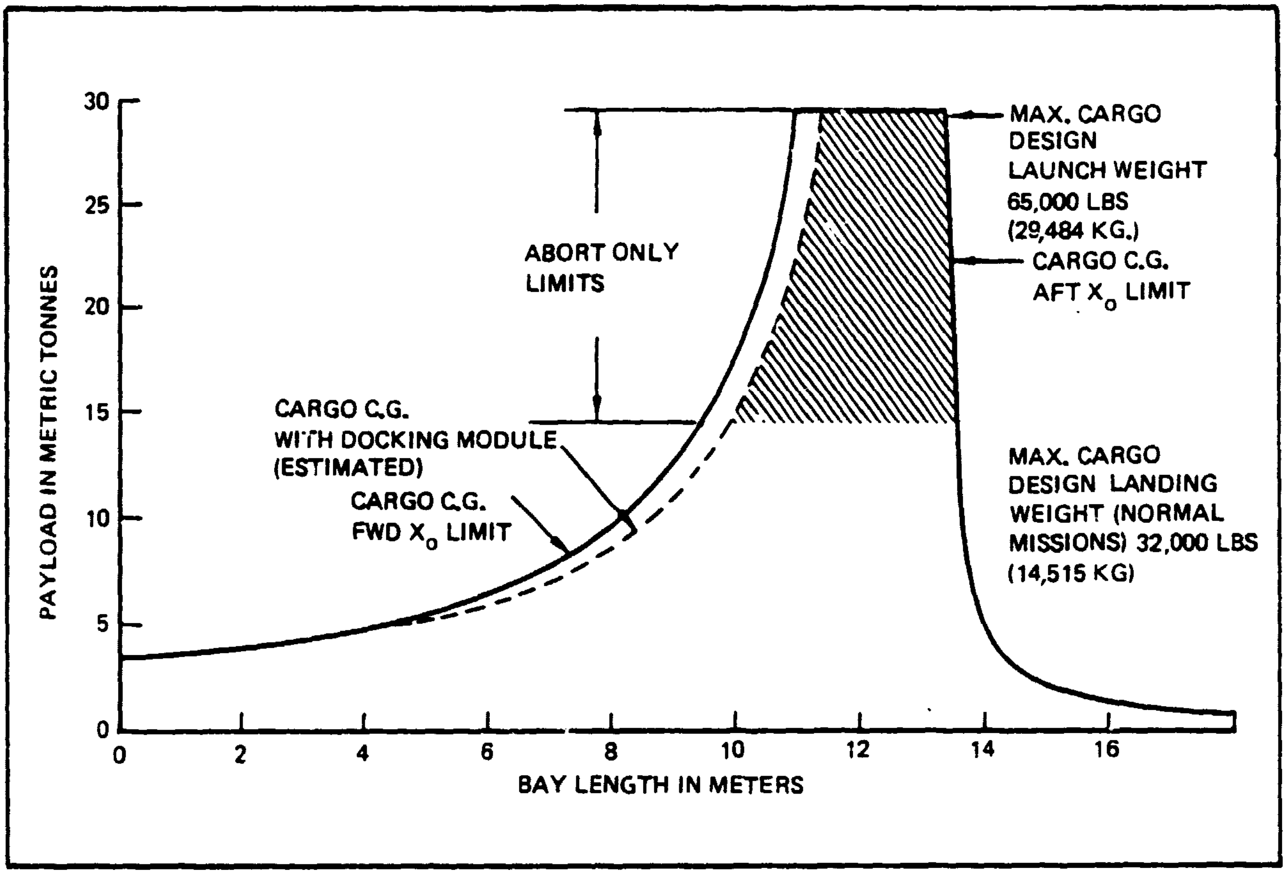


Figure 4.1-15 Shuttle Center of Gravity

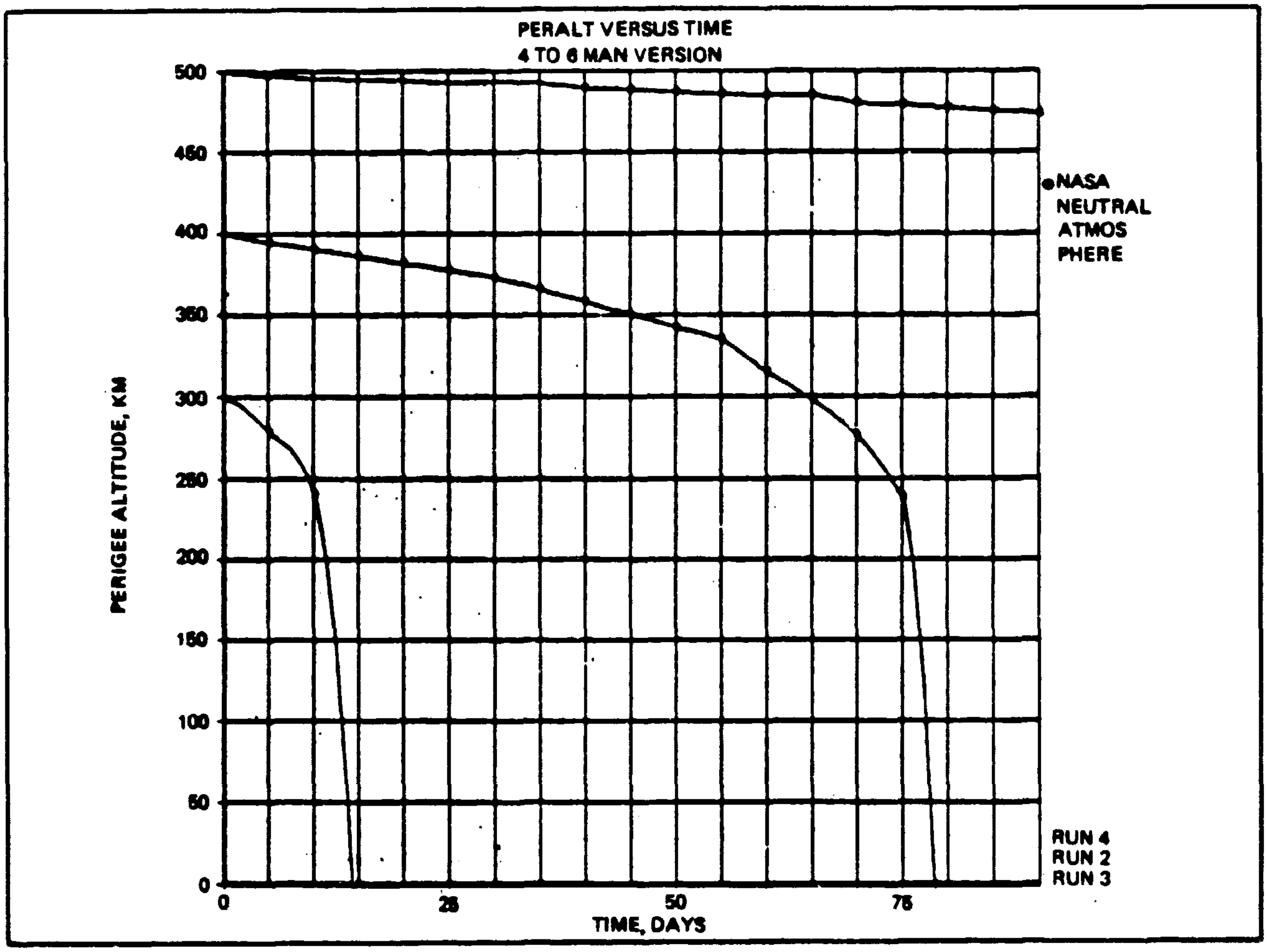
1.2.3 Architectural Assumptions, Design Stages and Growth

The intention of this section is to collect and highlight those features which contribute to the formation of space station architectures and may otherwise not receive this individual attention.

1.2.3.1 Assumptions

The creation of any design requires limits. The greater the understanding or resolution of those limits, the more responsive that design. So as not to prematurely inhibit the options yet provide guidance, a set of general assumptions was devised. The following is that list:

1. Shuttle delivered and serviced (No OMS Kit).
2. Low Earth orbit wth commonality between high and low inclination orbits.
3. Approximately 110,000 kg (50,000 lbs), 28 1/2° and 55,000 kg (25,000 lbs) polar.
4. 500 km (300 miles) at 28.5 degree and 400 km (240 miles) at polar.
5. 1990-Plus time frame.



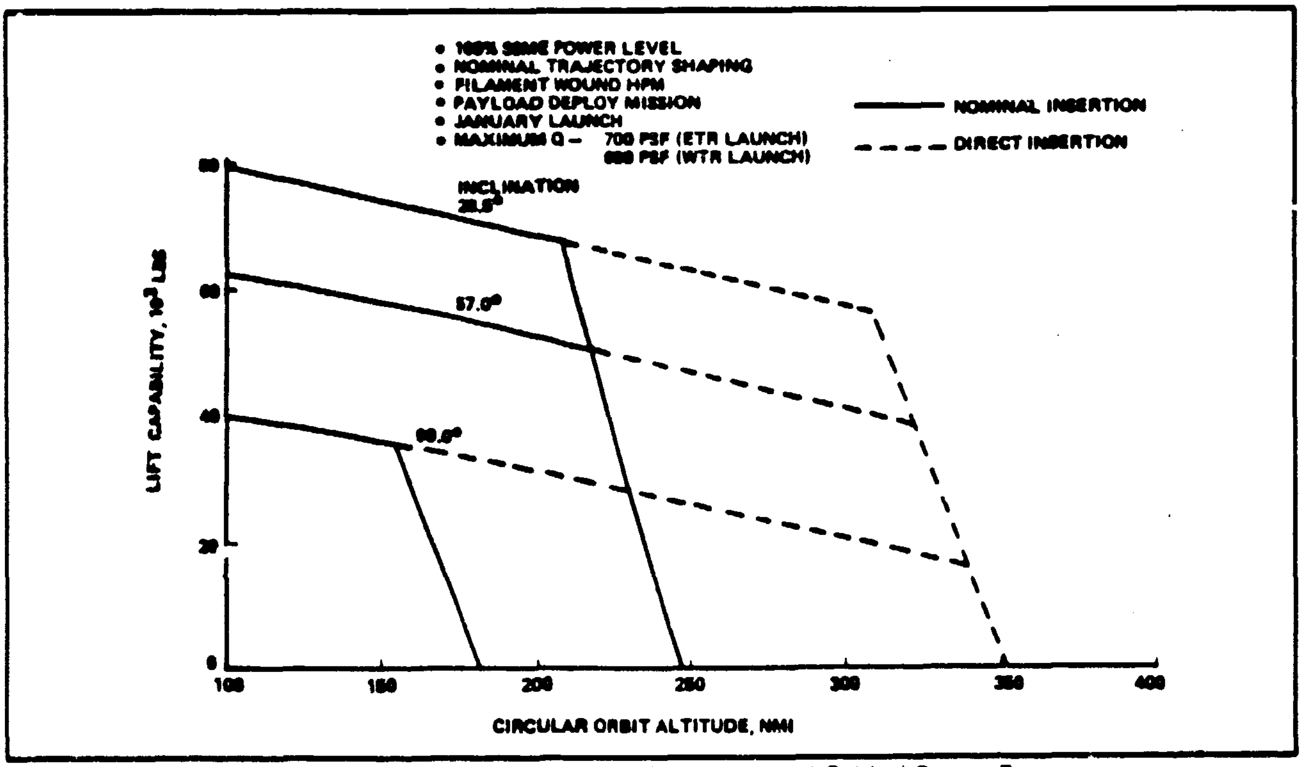


Figure 4.1-16 Direct Insertion Lift Capability and Orbital Decay Rates

6. Initial crew size 2-6 and transition to 12-13.
7. Provide reasonable growth strategies.
8. Must have 2 means egress, logistics module and air lock before being manned.
9. Earth oriented and inertial flight attitudes.
10. Solar array with fuel cell/battery power.

1.2.3.2 Stages of Analysis

For purposes of incremental evaluation of space station architectures, three levels of investigation were created. They are, symbolic, schematic, and conceptual design configuration (see fig. 4.1-17). The symbolic level is characterized by diagrams and is used to compare the general

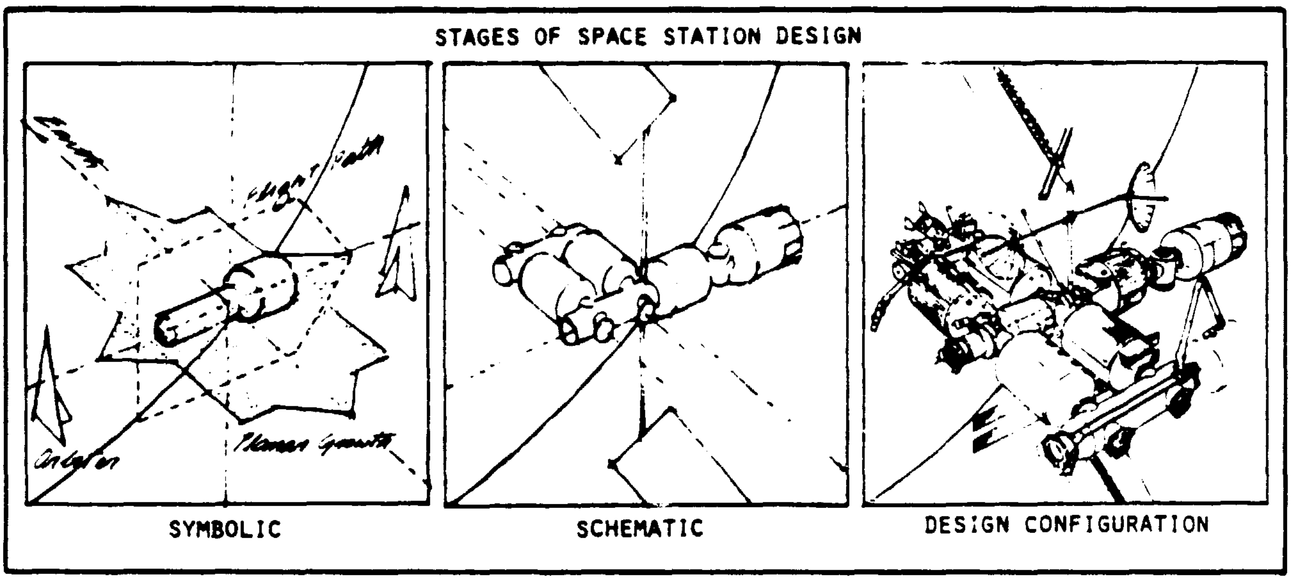


Figure 4.1-17 Stages of Analysis

features of one scheme to those of another (see fig. 4.1-18). The schematic representation displays the distribution of space station functions, proportional relationships and growth strategies. Finally, as discussed below, the conceptual design configuration examines proof of concept by delivery packaging, dimensions, weights, etc.

1.2.3.3 Level of Definition

The procedure followed for validation of architecture level ideas was to test the proposition by further definition. That is, the basic architectural tenets were taken to conceptual design configuration as demonstration of envisioned capability. By this method, one could evaluate:

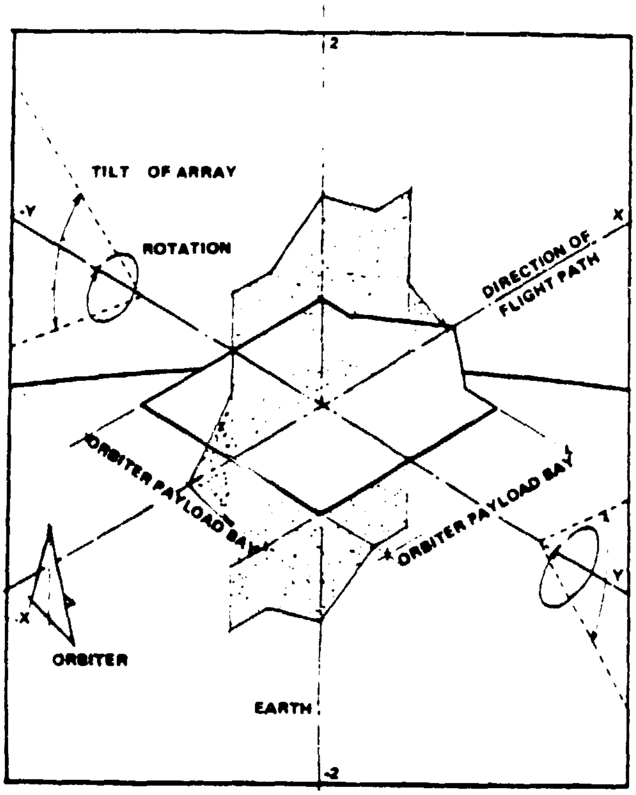


Figure 4.1-18 Space Station Architecture Symbology

1. Whether the capabilities and associated support equipment could be effectively distributed amongst the modules.

2. Whether the above could, in fact, be packaged within the shuttle payload bay.

3. Whether the module met shuttle payload weight and center of gravity requirements.

4. Whether the build-up sequence was in response to anticipated station capability (i.e., volume, data handling, power, thermal controls, etc.)

5. Whether the STS interface performed as intended - rendezvous and docking, misalignment envelope, control authority, payload handling, etc.

6. Whether any synergetic opportunities were available or overlooked.

The above is a partial list of many checks which are accomplished by taking architectural level ideas to a conceptual design configuration. In addition, cost models are not effective unless provided conceptual design level resolution. Accordingly, with this information, cost strategies can be integrated in the formative stages rather than as a modification to a developed idea.

1.2.4 Build-up and Growth

A space station which uses the shuttle for delivery and servicing will necessarily be an assembly of modules. Herein lies the challenge - to provide an economical man-rated station which can grow in response to mission needs.

Planning for space station growth is a complex assignment. It requires an understanding of the type, rate and limits of growth (see fig. 4.1-19). Owing to the integrated nature of a space station, each system needs to be examined for its impact as change occurs. Additionally, some

ANTICIPATORY	–	Space station features which are inherently difficult or not cost-effective to grow-reaction control system, solar array rotary power transfer, etc.
ENHANCEMENT	–	Systems which are designed to accommodate improvement – closure of EC/LS, up-rating data management system, etc.
COST SENSITIVE	–	Demand driven supply of space station attributes – expensive solar arrays should closely match and not exceed electrical power demand.
EXPANSION	–	Grow which is an enlargement of the space station and implies adaptability – addition of a module, RMS, etc.

Figure 4.1-19 Types of Space Station Growth

systems must pay an early penalty in order to accommodate programmed growth. An example is the power transfer connection between a solar tracking array and the earth oriented station. It makes more sense to oversize the joint for initial loads than to interrupt service and perform on orbit replacement to incrementally satisfy an increasing demand. Alternately, other systems should grow only on demand in order to more evenly distribute the cost. This is particularly true with solar arrays. Furthermore, some change should accommodate not only system expansion but enhanced performance. The gradual closure of the environmental control and life support system is an example of this type of growth.

The impetus behind the initial space staion is in providing occupancy (within requirements) for the fewest number of shuttle deliveries. Growth beyond this point is mission driven until economies of effectiveness can be better served by building another station.

General space station growth geometries come in three shapes, planar, branched and three-dimensional.

Planar growth provides ample operations work space, two means of egress, build-up by shuttle/remote manipulator system and fair to good thermal view factors. On the other hand, the inertial differences can outgrow the control moment gyro inertial pointing capability. (See fig. 4.1-20).

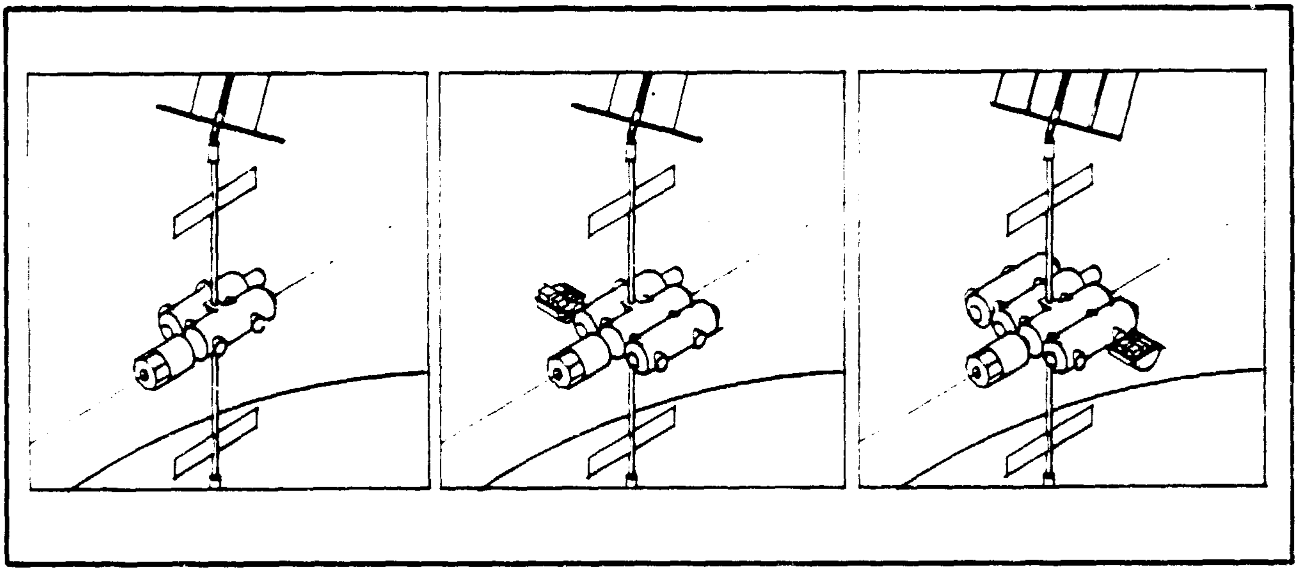


Figure 4.1-20 Planar Space Station Growth

The branched geometry affords indefinite growth, greater flexibility for instrument pointing and attachment and fair to good thermal characteristics. However, operations work space is cut up making mobility difficult, it lacks dual egress paths and it tends toward large inertial differences. (See fig. 4.1-21).

A three dimensional growth strategy provides two or more egress paths and inertial symmetry permits all orientations. Conversely, the operational work space is restricted with difficult mobility, it presents assembly difficulties, has poor thermal view factors and is limited in growth. (See fig. 4.1-22)

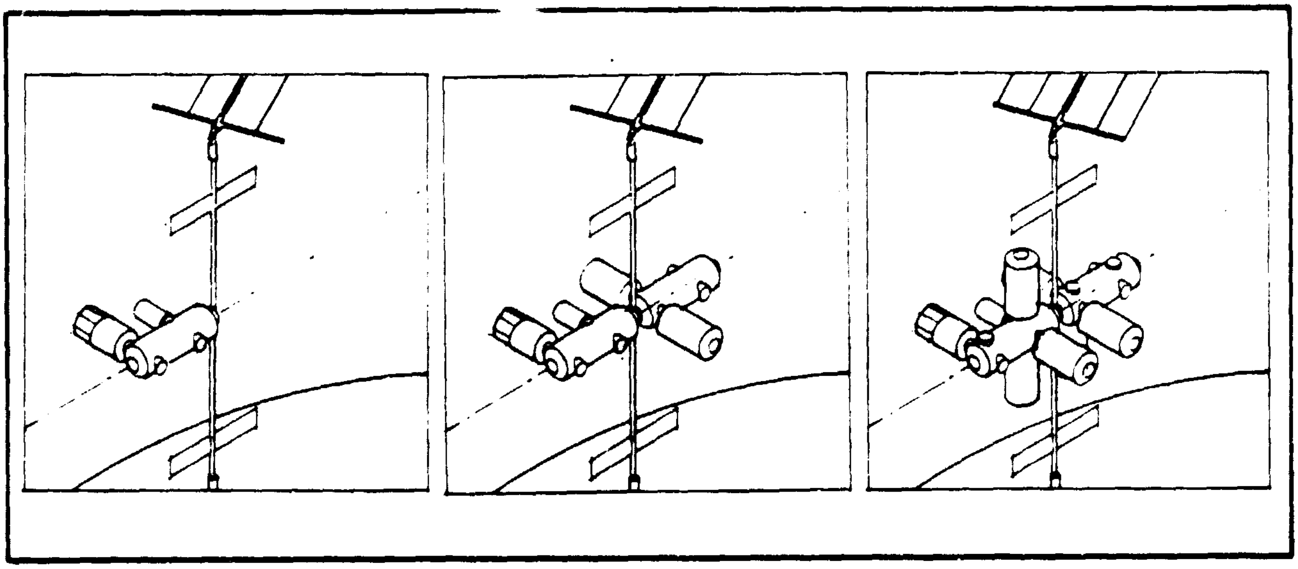


Figure 4.1-21 Branched Space Station Growth

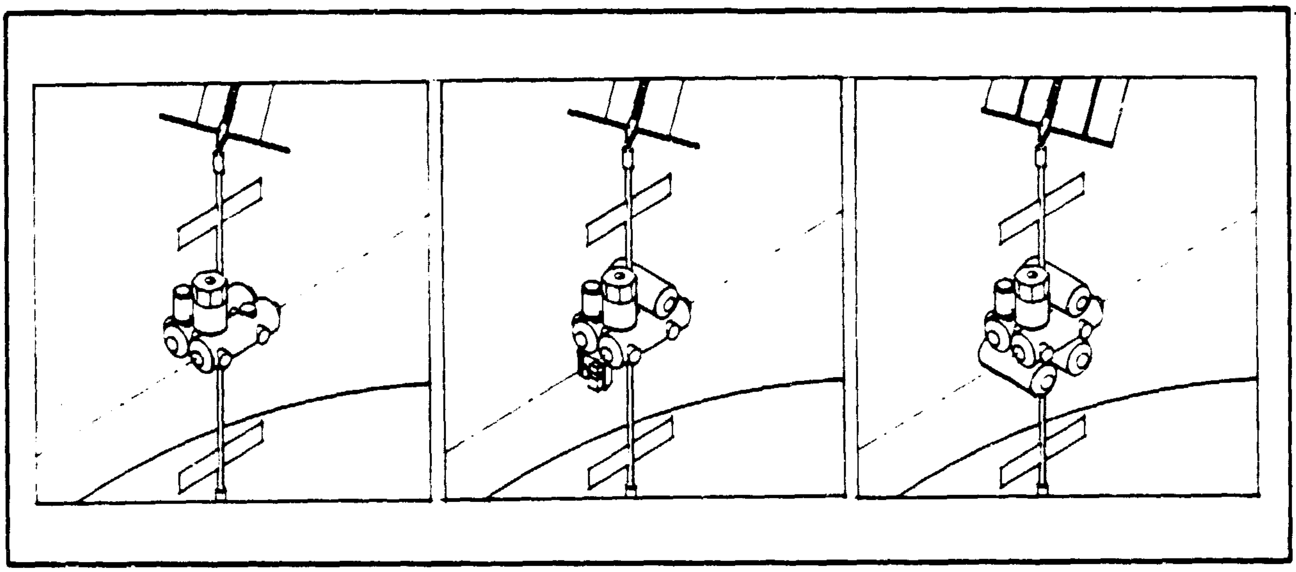


Figure 4.1-22 Three-dimensional Space Station Growth

1.2.5 **Contingency** - The integration of provisional or back-up systems is a significant factor in space station architecture. Although not thoroughly determined, we have anticipated a proof of concept approach which contains provisional measures during a checkout period then transitions to an operational mode with its own contingency provisions. Each architecture includes a back-up command/control station, in addition to retaining the ground control option. Also, associated with the back-up command/control are accommodations for food, EC/LS, personal hygiene and sleeping. Consistent with the conceptual level of space station architecture in this

study, additional contingency provisions including redundancy, have been included under an adopted fail-operational approach.

1.2.6 Commonality - Commonality with respect to space station design is more a means to satisfy on-orbit repair, maintenance and servicing, than reduce manufacturing costs. It is unreasonable to adopt the assembly-line techniques associated with high production units when the number of modules comprising this initial shuttle delivered space station is seen as few. However, where possible, standardization and cost savings commonality will be incorporated. This is accomplished with an understanding of economizing through flight proven hardware, as well as, improving particular operations in areas of technology development. As shown in figure 4.1-23, architectural level commonality is envisioned as a complete module common to either high or low inclination orbits (incremental architecture) or common subsystems assembled for either inclination orbit or shared modular elements (unified and derivative architectures).

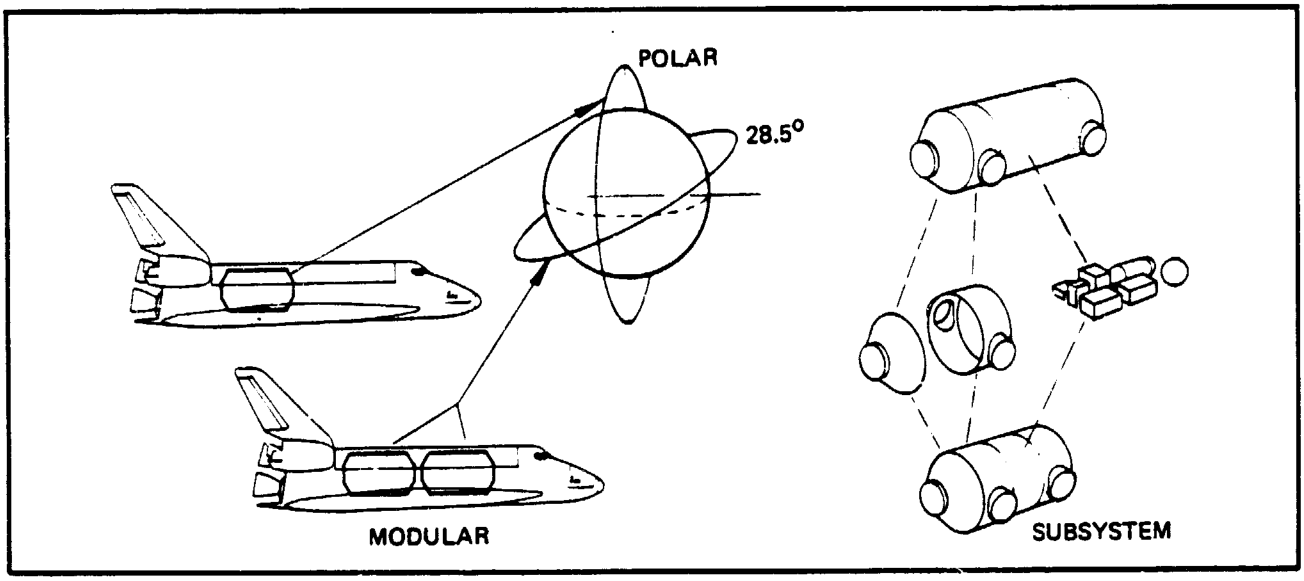


Figure 4.1-23 Two Methods of Commonality

1.2.7 Reliability - The reliability of space station operations is both a function of hardware and procedure. The standards or specifications for the hardware should consider the criticality in performance in conjunction with repair, replacement and cost. The emerging technologies of expert systems can extend the built-in-test-equipment (BITE) capability and produce enhanced reliability.

Common sense, reinforced by our crew systems analysis, indicates that accessibility is an essential feature contributing to long term reliability. Figure 4.1-24 demonstrates a concept of simplified subsystem layout incorporating accessibility as a major feature. The mechanical/

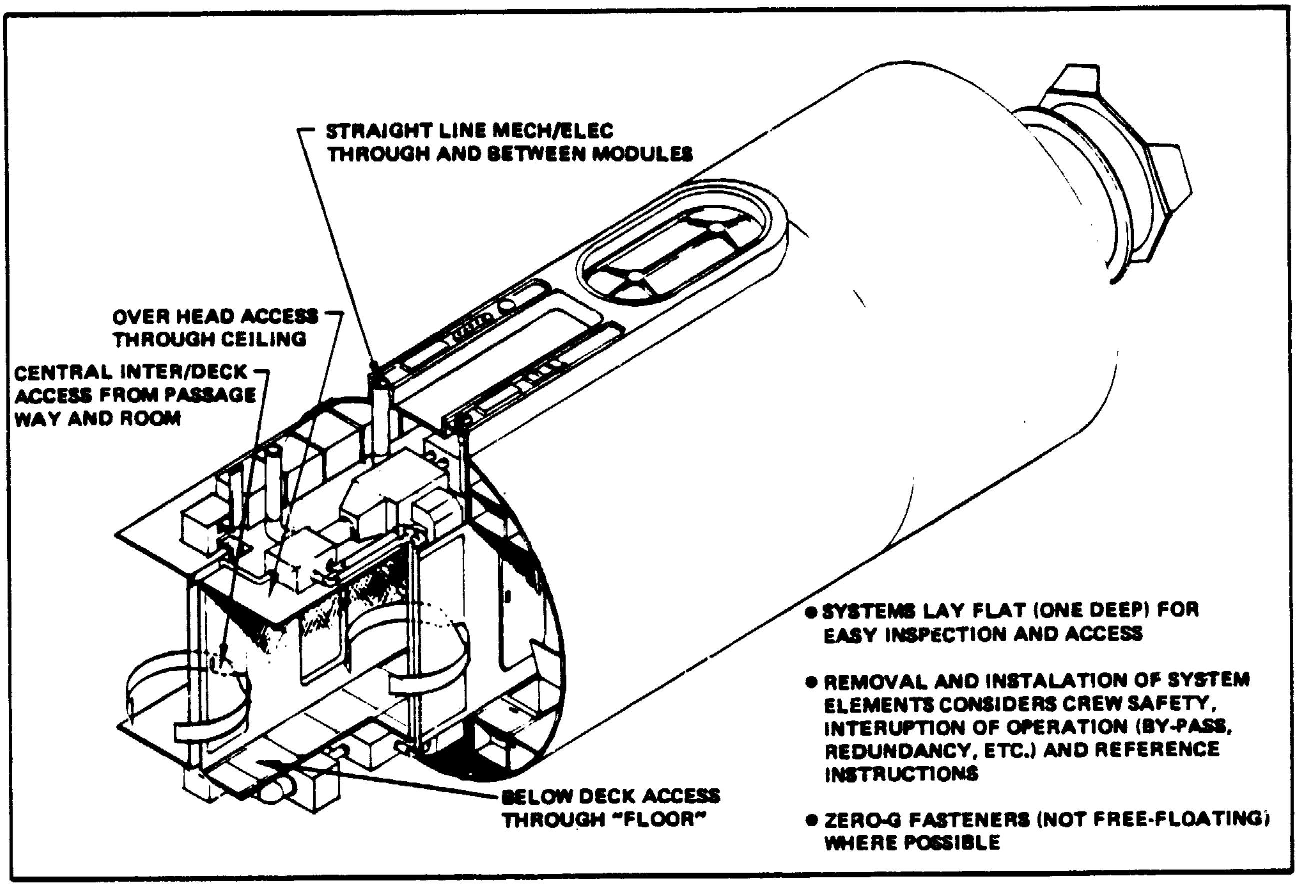


Figure 4.1-24 Easy On-orbit Access to Subsystems

electrical runs within the module are central and straight. They are arranged flat and thin so the elements are only one unit deep (no hidden components) and have crew access from two sides.

To this extent we have integrated reliability in the architectural level of space station definition.

1.2.8 Contamination - A frequently-stated mission need was for a low contamination environment. One approach is to put contamination sensitive systems on a free-flyer platform. This, however, complicates servicing operations and requires EVA for essentially all servicing.

We considered several measures to reduce space station contamination environments to a level acceptable for mission operations. Orbit makeup propulsion could be provided by resistojets using either hydrogen or EC/LS surpluses. At the 500-kilometer altitude for the low inclination station, infrequent orbit makeup maneuvers at higher thrust could utilize the integrated hydrogen oxygen system that we have incorporated.

Airlock outgassing is a source of contamination. Even though airlocks will be pumped down to conserve atmosphere, the minimum practical pressure will be 1/2 to 1 psi. When the airlock door is open, outgassing will issue from the airlock walls for a significant time. It is important to locate airlocks to eliminate direct paths from the airlock door to sensitive instruments.

Elimination of the water boiler from the EVA suit is important. The present shuttle toilet vents water vapor and other contaminants overboard. A no vent toilet would significantly improve atmospheric contamination.

Pressurized modules should be designed for low leakage. Historically, space station leakage specifications have been set at the resupply nuisance level, e.g. several kilograms per day. The leakage specification should be reduced to that consistent with good manufacturing and quality control. Fig. 4.1-25 presents a summary of minimum contamination approaches.

RESISTOJETS USING GASES FROM INTEGRATED ELECT. RCS EL/LS (H_2, CO_2)
LOCATION OF AIRLOCKS
ICE PACK SUIT
NO VENT TOILET
LOW LEAKAGE DESIGN
CMGs

Figure 4.1-25 Minimum Contamination Strategy

Around the ancient track marched, rank on rank
The army of unalterable law.

GEORGE MERIDITH

1.3 SPACE STATION ARCHITECTURE

The organization of selected architectures conforms to the following format:

1. Description/Objective
2. Elements
3. Growth
4. Attributes

Three architectures have been identified. These are incremental, unified and derivative. Each represents a careful study in compromise and develops according to set of mission objectives. (See fig. 4.1-26)

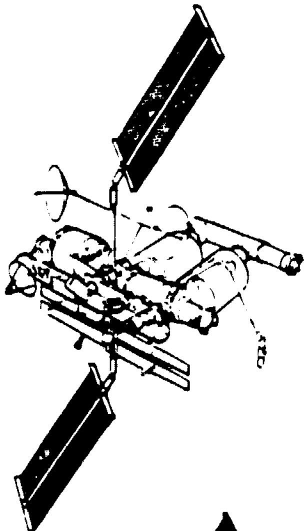
1.3.1 Incremental Architecture

The composit system architecture for the space station(s) and associated free flyers is shown in time-phased growth in fig. 4.1-27.

1.3.1.1 Description/Objectives

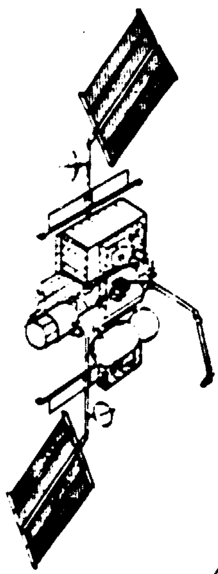
The term incremental space station refers to the capability of either on-orbit or "factory" assembly of discrete modular elements. This affords the option of being able to construct space stations for both low and high inclination orbits with the same pieces while adhering to the significant differences in shuttle launch performance to these orbits.

Radiation - Owing to the interaction between solar activities and the earth's magnetic field, a polar orbit station is subject to greater radiation levels than a low inclination station (see fig. 4.1-28). Therefore, the polar space station architecture includes a radiation storm shelter for the crew. Fig. 4.1-29 shows the factors contributing to its conception while a representation of design is shown in the incremental architecture command/control module.



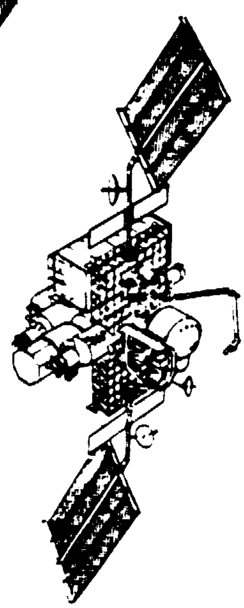
INCREMENTAL

- DRIVEN BY HIGH ORBIT OBJECTIVES
- COMPRISED OF ACTIVITY-SPECIFIC MODULES



UNIFIED

- SATISFIES LOW INCLINATION ORBIT OBJECTIVES
- COMPRISED OF COMMON MODULE - OUTFITTED FOR PARTICULAR ACTIVITIES



DERIVATIVE

- PROVIDES ALTERNATIVE BUILD-UP SEQUENCE USING UNIFIED ARCHITECTURE ELEMENTS
- CAN BE FLOWN AS UNMANNED PLATFORM

Figure 4.1-26 Three Space Station Architectures

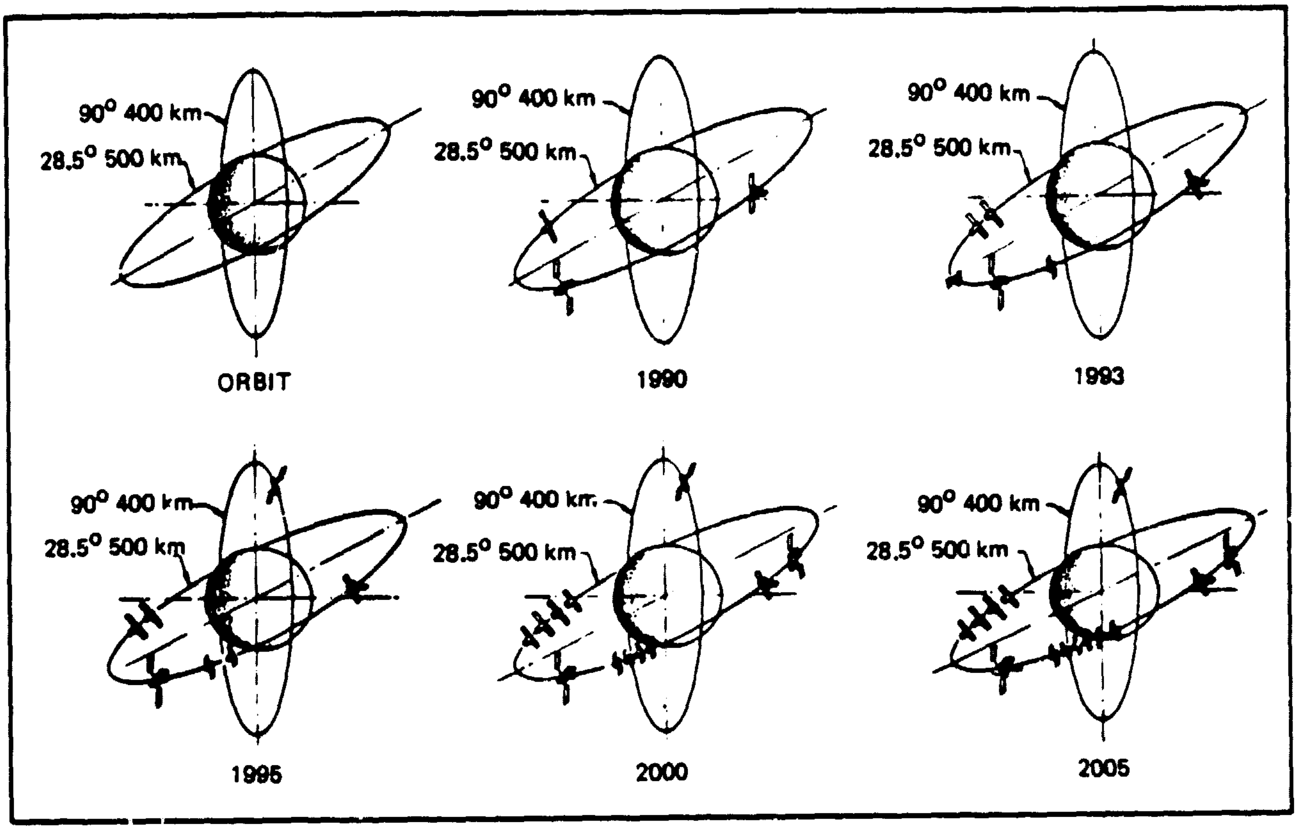


Figure 4.1-27 Time Phased Space Station System Architecture

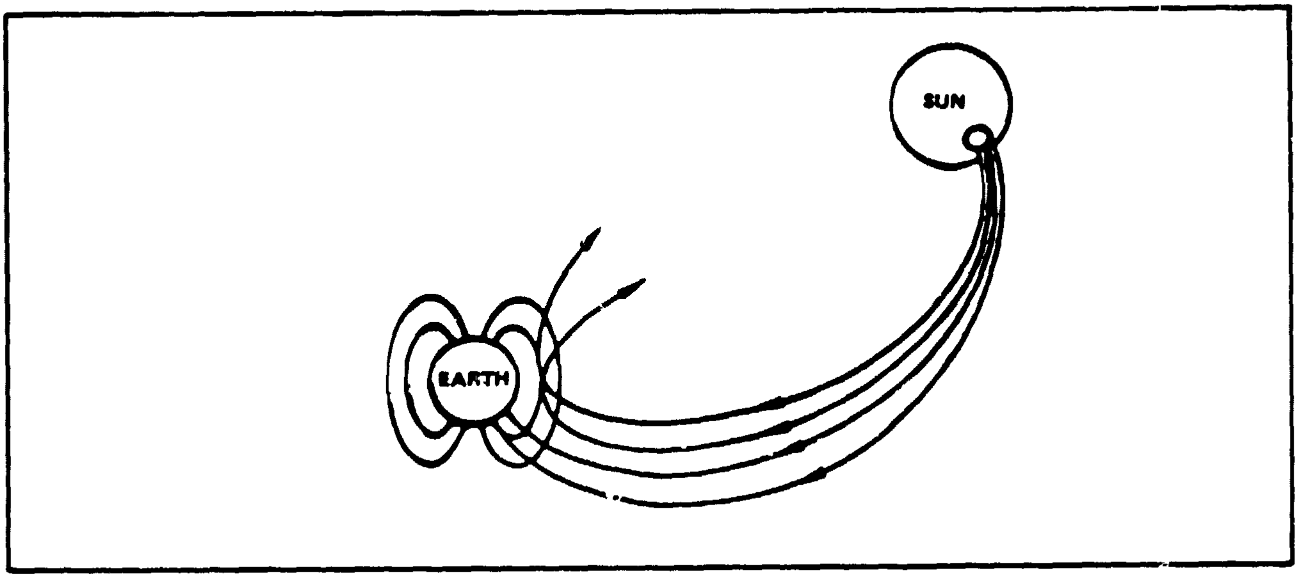


Figure 4.1-28 Solar Cosmic Ray and Earth Interaction

- LOW-INCL., LOW-ALTITUDE: NO SPECIAL REQUIREMENTS
- HIGH-INCL., LOW-ALTITUDE: NEED A SOLAR FLARE STORM SHELTER ≈ 20g/CM^2
- HIGH-ALTITUDE: NEED A SOLAR FLARE STORM SHELTER ≈ 30g/CM^2

Figure 4.1-29 Radiation Protection

The zoning assignment supporting the incremental architecture is: (See fig. 4.1-30)

1. The service functions are performed by a single, centrally located module.

2. Command control is provided within a separate module axially aligned to the service module.

3. Crew accommodations are distinguished by activity groupings (quiet, social, etc.) and when appropriate are located in separate modules.

4. Mission support is accomplished by either a strongback module or lab module located adjacent to the service module and earth oriented.

5. Crew hygiene functions are positioned within the logisitics/resupply module.

1.3.1.2 Elements

Module sizing is a result of sensible activity assignments for shuttle payloads to a high inclination station (see fig. 4.1-31). This, in conjunction with module commonality for the low inclination architecture, resulted in:

1. A service module with a geometry responding to the accommodation of requisite hardware, orbiter payload envelope and destination.

2. Identically sized pressure vessels which can be delivered individually or together.

3. Specialized modules that satisfy particular mission or operations functions.

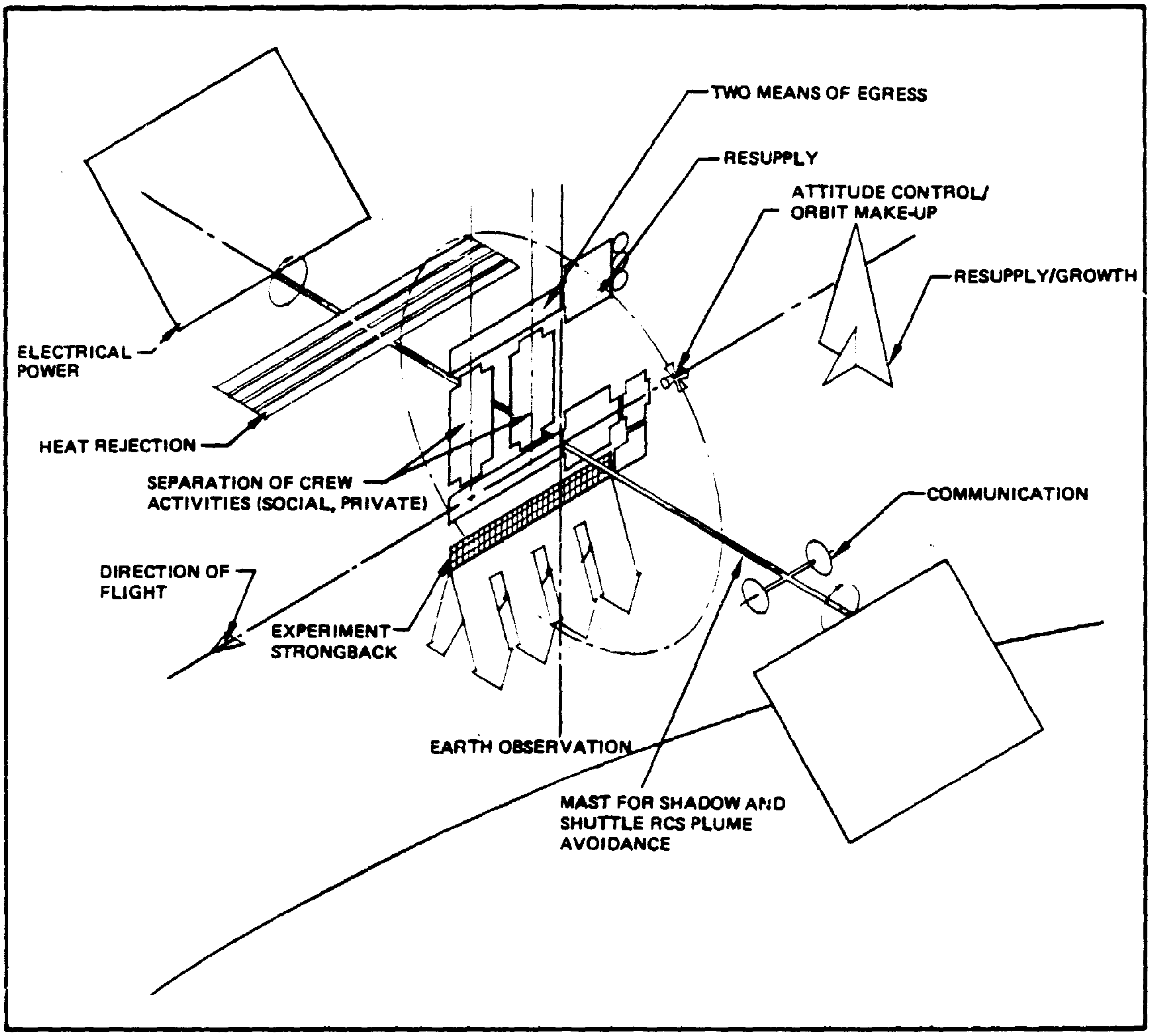


Figure 4.1-30 Zoning of the Incremental Architecture

The overall system is assembled as shown in figure 4.1-32 with an alternate version in figure 4.1-33. The major elements which make up the incremental architecture are:

1. Service Module, figure 4.1-34 - supplies electrical power, attitude control, thermal control, communications, EC/LS and the structural/utility interface for station build-up.
2. Command/Control, figure 4.1-35 - is the operations decision center, stores and reconditions EVA suits and provides a storm shelter for radiation protection in the high inclination environment.

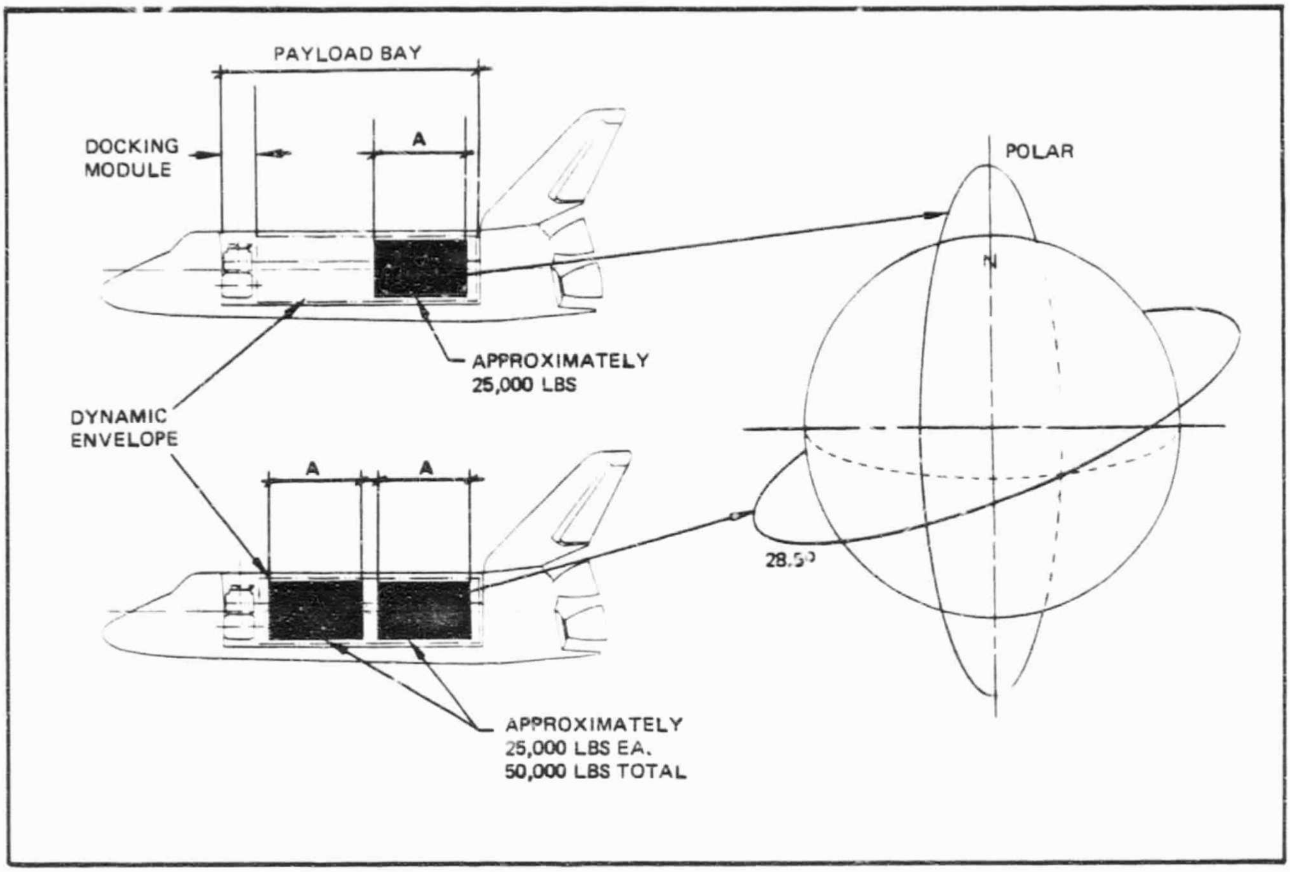


Figure 4.1-31 Module Sizing Rationale for the Incremental Architecture

3. Habitat Module - provide private crew quarters, hygiene equipment, health maintenance support, galley, dining and other crew systems equipment. The Habitat Module shares a common pressure vessel with the Lab Module and is shown in Fig. 4.1-36.
4. Lab Module - has the same pressure envelope as the habitat modules but contains the work space and equipment for research.
5. Experiment strongback Fig. 4.1-37 - is the combined structure and identified experiments for polar orbit missions.
6. Air-lock - pressure vessel allows transition to the space environment.
7. Logistics/Resupply Fig. 4.1-38 - is the means of replenishing consumables. It provides internal access to both cold and dry stores and transports hazardous materials externally. Since the polar orbit payload is mass-limited, the initial station distributes the activities amongst all modules with the logistics vehicle serving as bathroom in the early configuration.

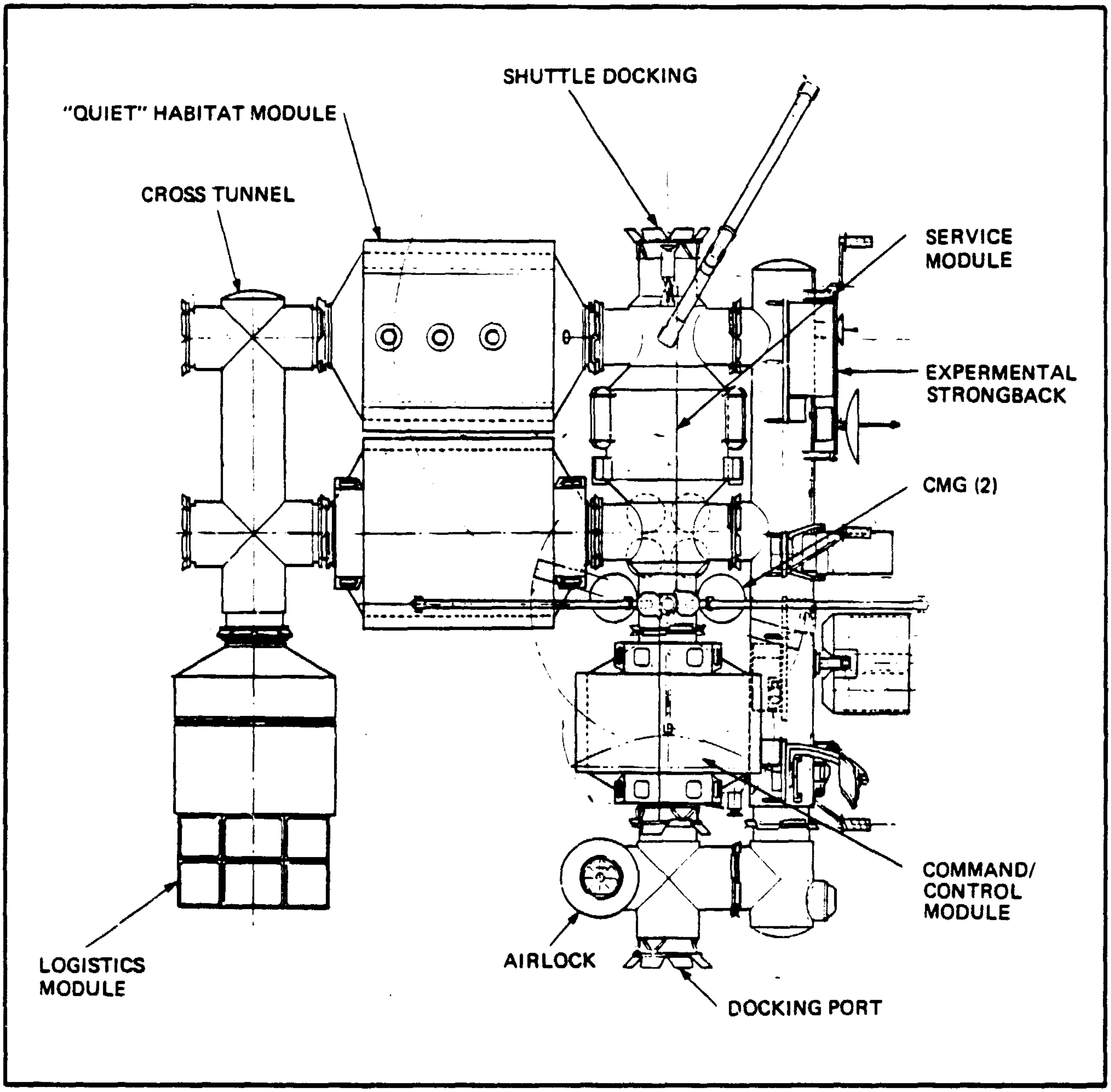


Figure 4.1-32 Overall View of Incremental Space Station Architecture

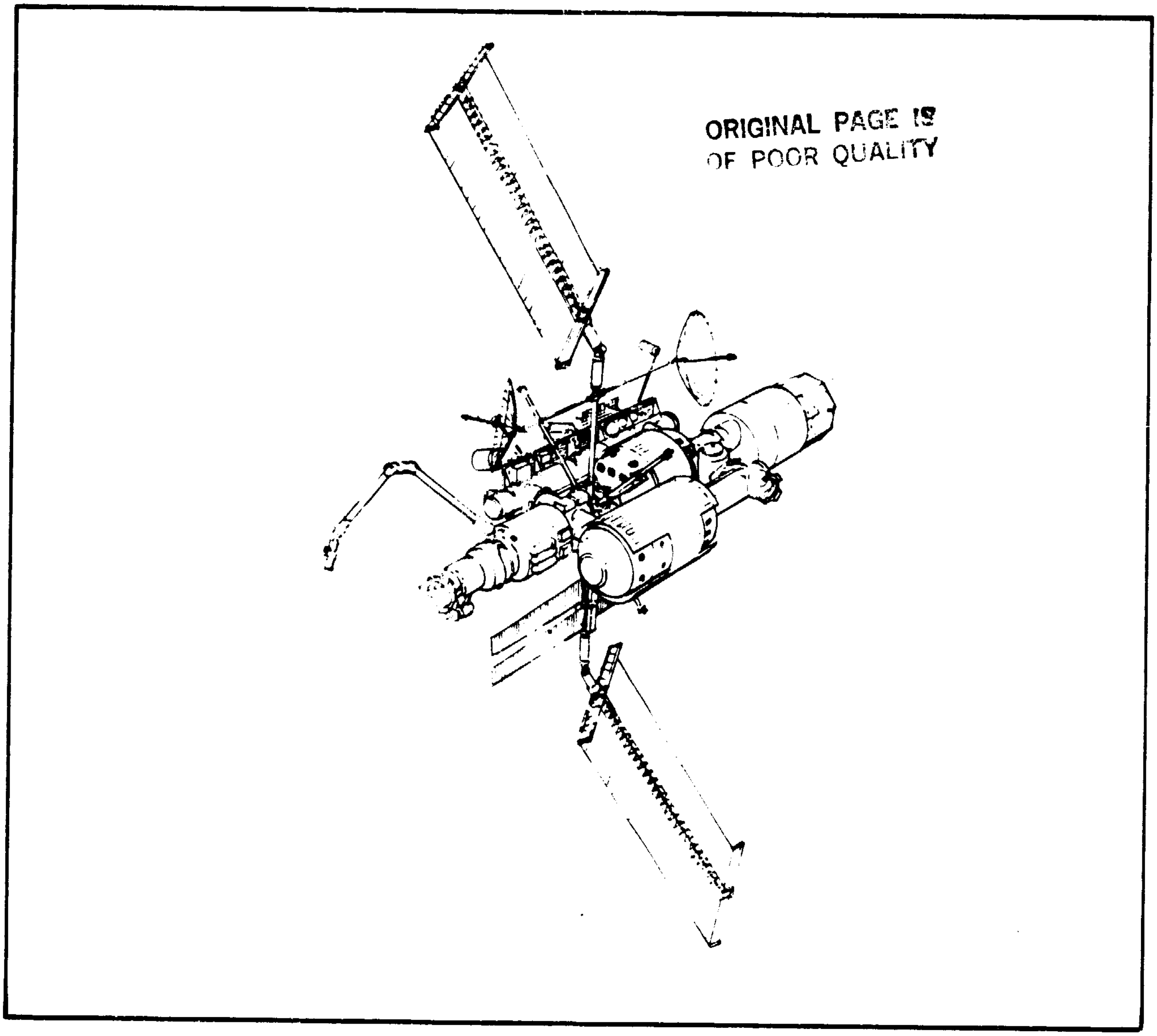
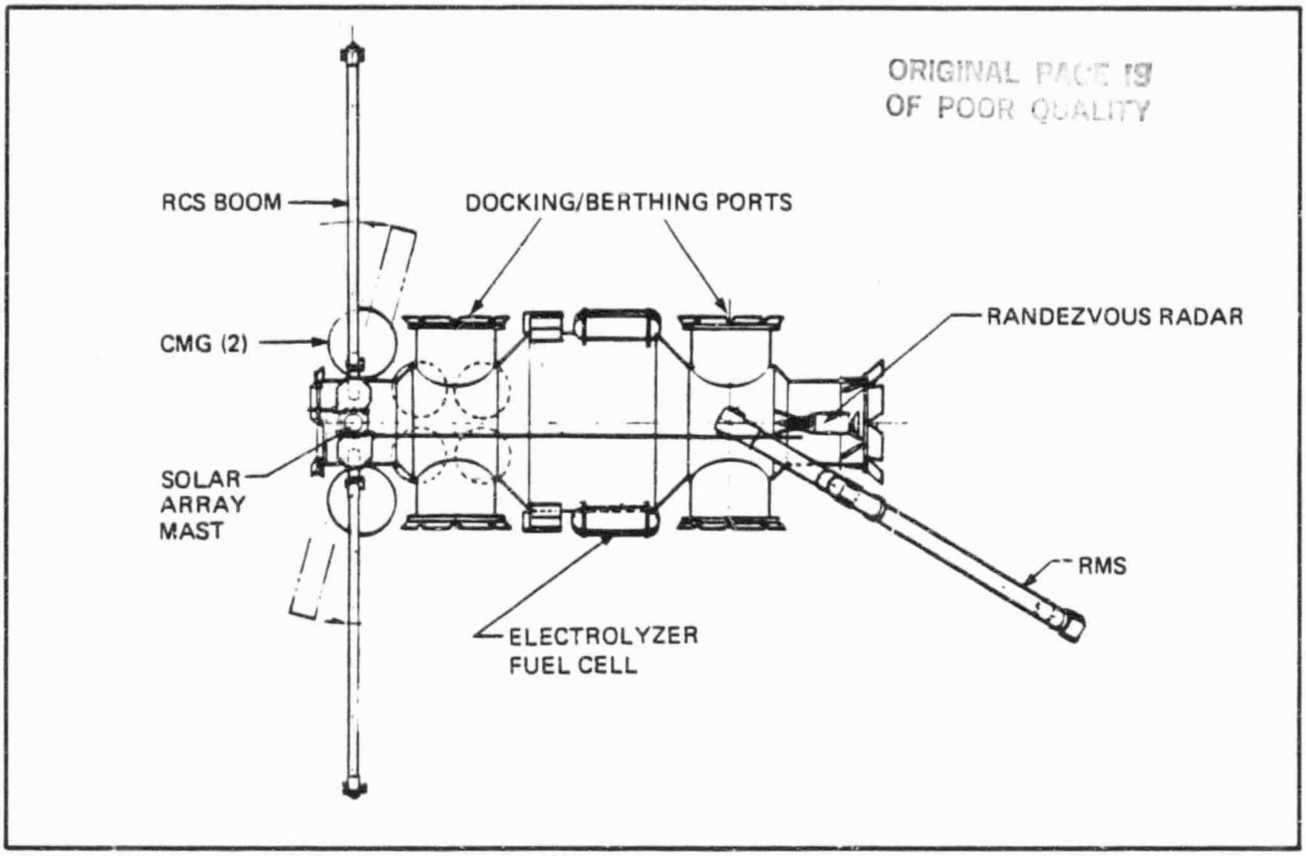


Figure 4.1-33 Alternate Arrangement for the Incremental Architecture



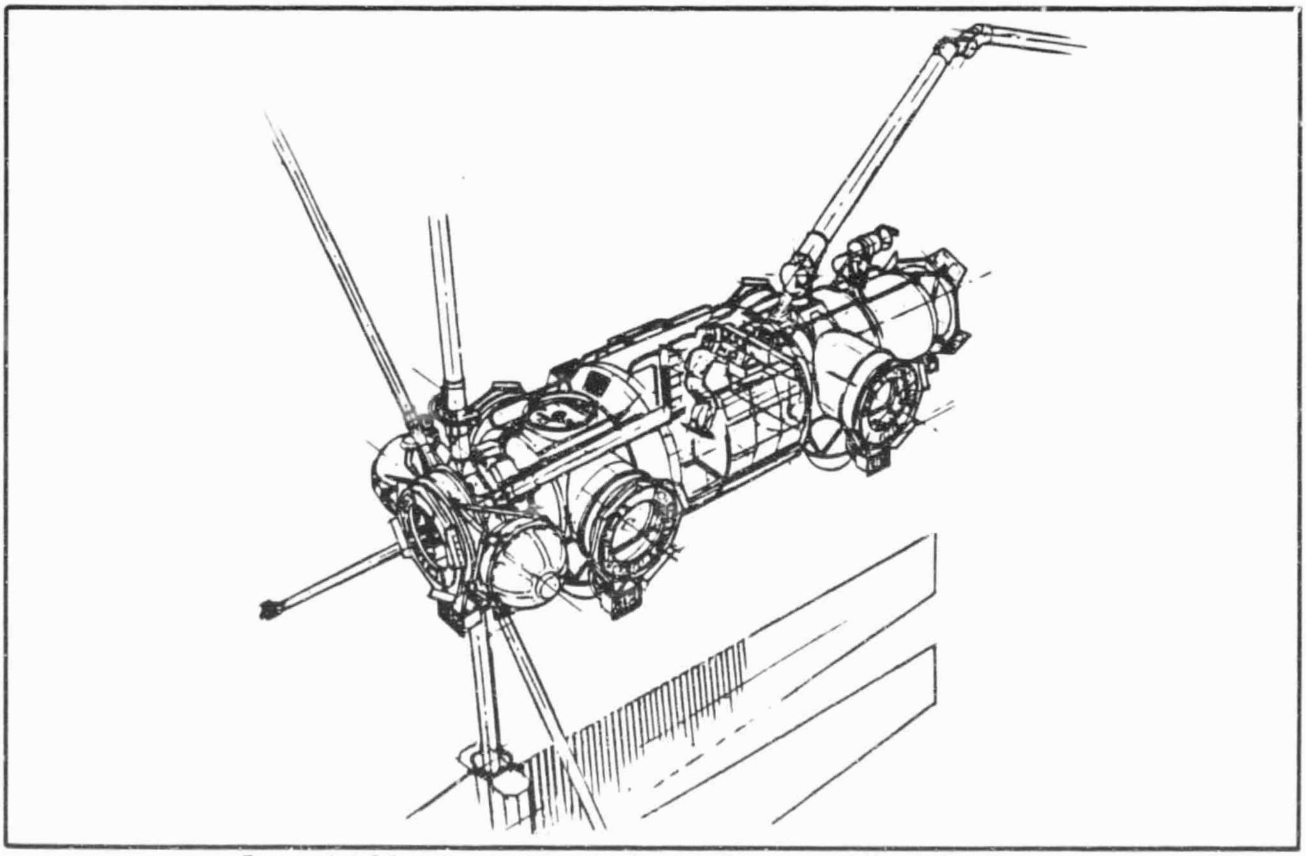


Figure 4.1-34 Service Module for the Incremental Space Station

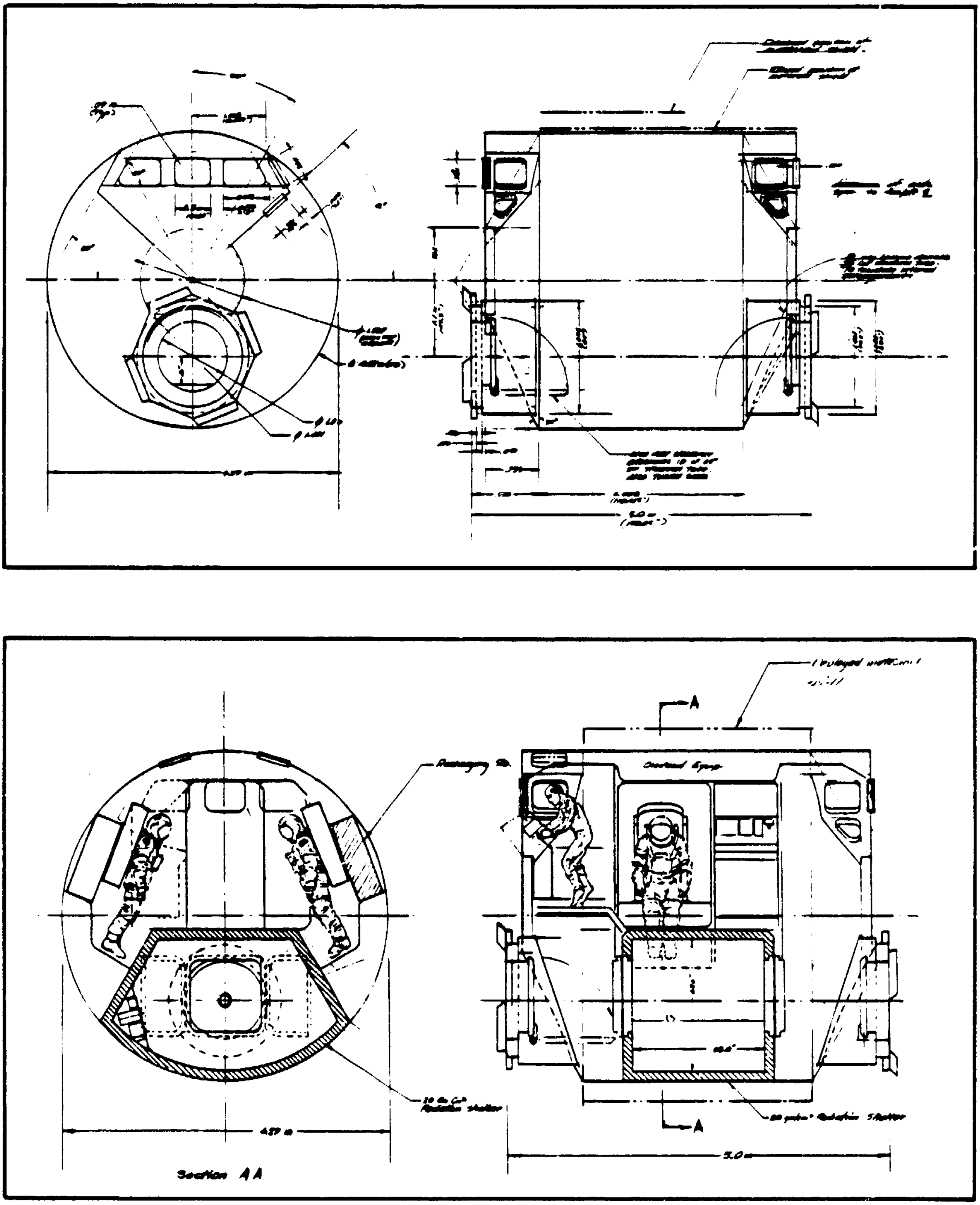
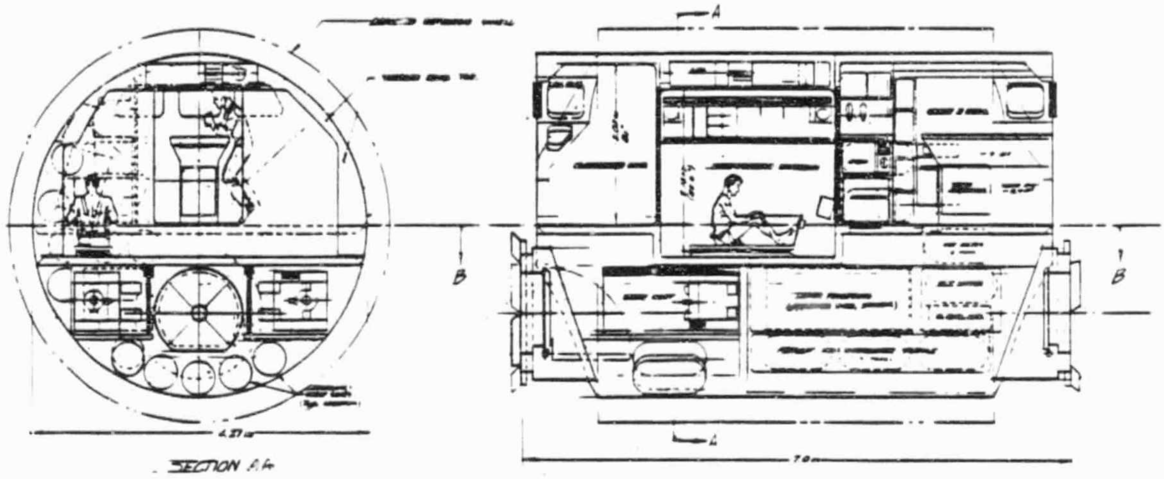


Figure 4.1-35 Command/Control Module for the Incremental Space Station



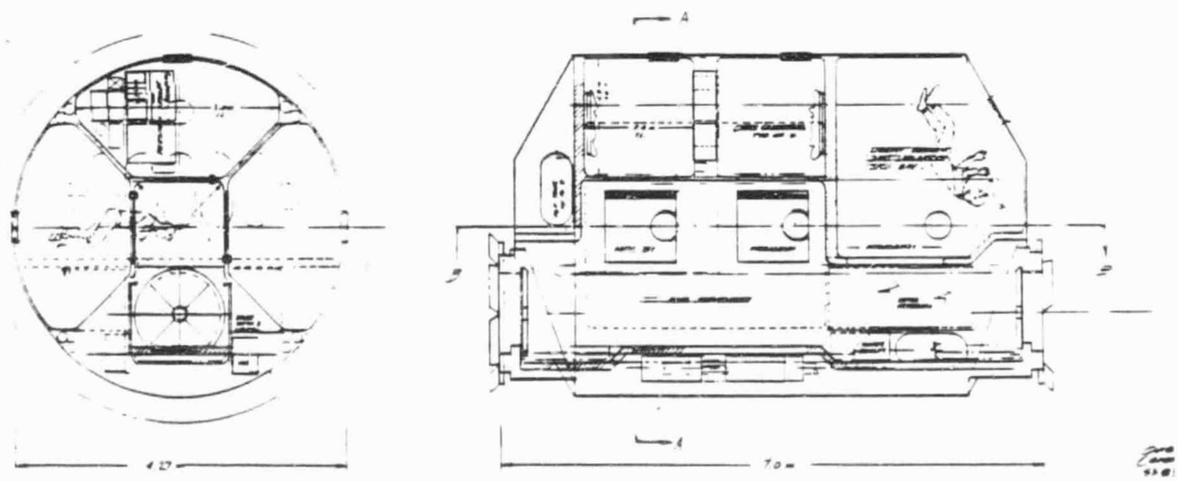


Figure 4.1-36 Habitat and Lab Modules for the Incremental Space Station

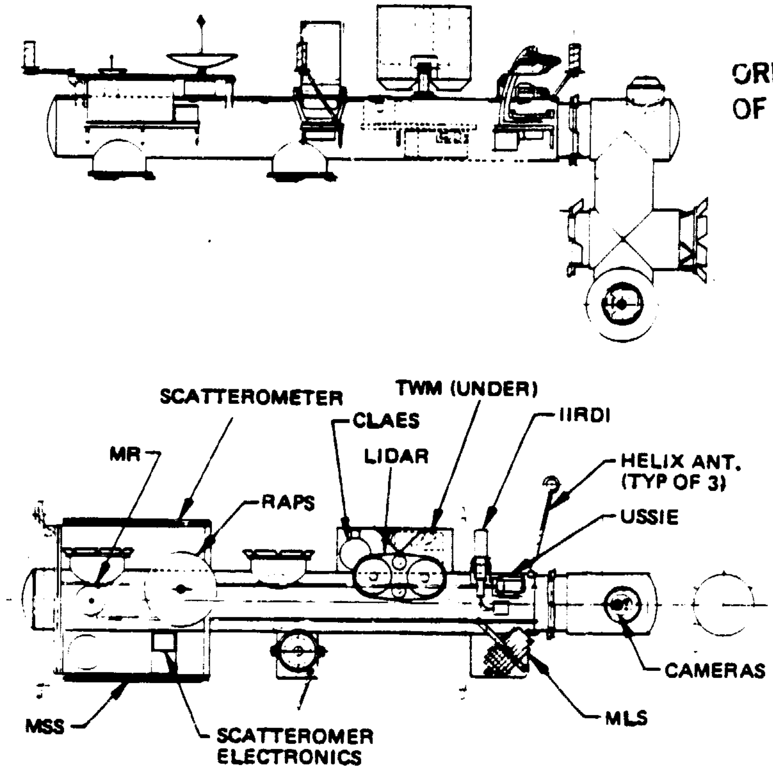
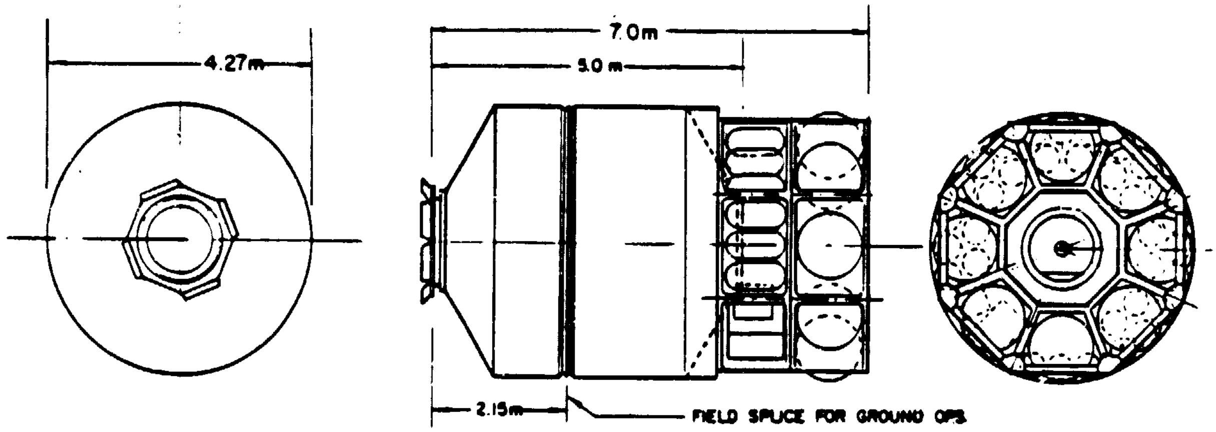


Figure 4.1-37 Experiment Strongback for the High Inclination Missions



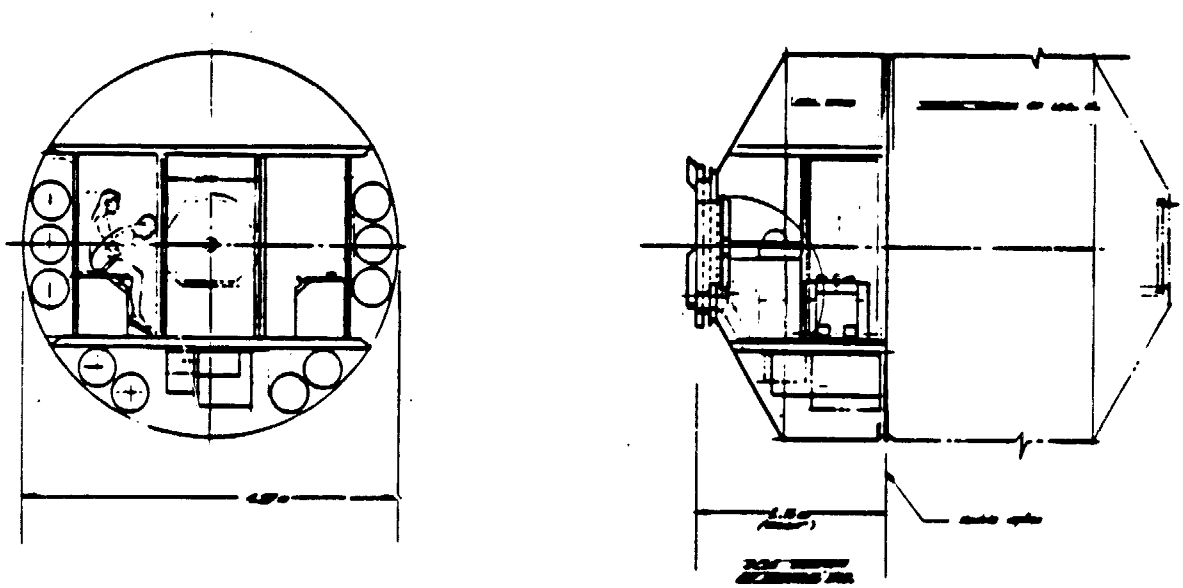


Figure 4.1-38 Logistics/Resupply Module for the Incremental Space Station

1.3.1.3 Growth

As mentioned earlier, the incremental assemblies of this architecture can either be performed on orbit or in the factory depending on orbital destination. The high inclination station grows in the following manner: (see fig. 4.1-39)

1st Delivery - The service module is carried from western test range into a 400 KM circular orbit by the shuttle. It deploys solar arrays for electrical power, radiators for thermal control, antennas for RF link, and RCS thrusters for attitude control (cmg's are included to assist in this function). These features provide module control from the ground prior to the crew's arrival.

2nd Delivery - The following shuttle delivery brings the command/control module. Using the shuttle RMS the two are joined and await arrival of the next module.

3rd Delivery - Along with the logistics/resupply and airlock module, a three man crew is transported to the awaiting spacecraft. For the initial operation, activities have been distributed in favor of early occupancy and a more evenly distributed launch weight assignment. Therefore, the personal hygiene responsibilities are incorporated into the logistic/resupply module.

4th Delivery - The next shuttle supply brings an experiment strongback. This is the support structure for a collection of high inclination experiments.

5th Delivery - The incremental space station is enlarged by the addition of a habitat module on next shuttle delivery.

6th Delivery - Another habitat module further enlarges and improves the station on the sixth delivery.

Further growth or reconfiguration occurs on a demand basis.

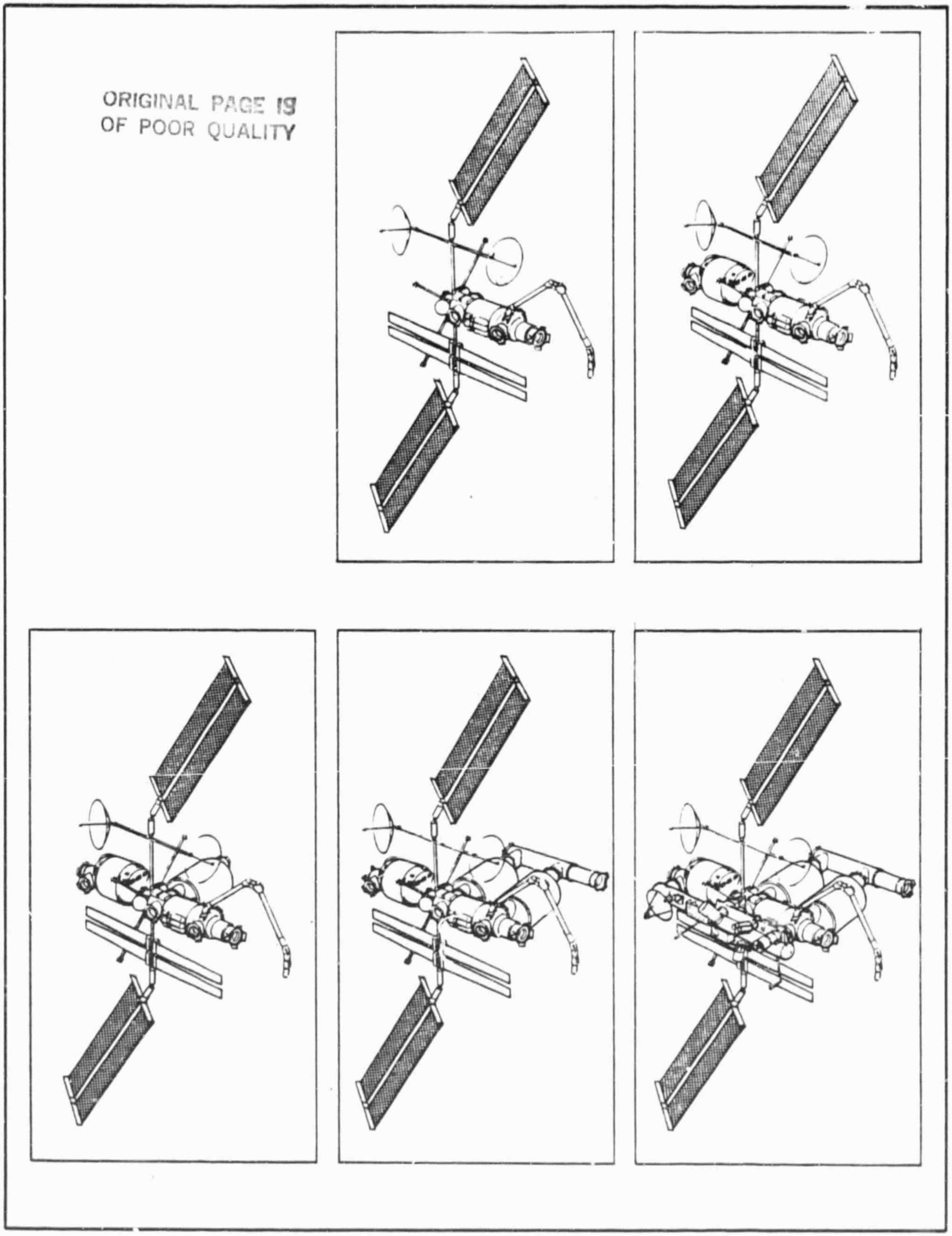


Figure 4.1-39 Build-up Sequence of the Incremental Architecture

1.3.1.4 Attributes

Attributes of the incremental space station architectures are: (See fig. 4.1-40)

1. Module commonality for high and low inclination orbits.
2. Service module with back-up command/control.
3. Integral radiation storm shelter.
4. Separation of social and private crew functions.
5. 360° view command/control module.
6. Combined RCS, cmg reaction control system.
7. Solar array, electrolyzer/fuel cell electrical power system.
8. Back-up command/control

1.3.2 Unified Architecture

1.3.2.1 Description/Objectives

The term unified space station is used to describe the concept of combining the typically separated functions of utility supply and habitation into one hybrid module. This union satisfied the major objective of providing a man-rated station for the fewest shuttle deliveries without compromise to mission performance. In addition, the unified space station incorporates adaptive planning, whereby differing mission demands and funding profiles can be accommodated within the same architecture. Consequently, either conservative or aggressive mission models can be realized within one space station architecture.

The zoning for the unified architecture is shown in Fig. 4.1-41 and is characterized by the following:

1. The principal utility supply and initial crew quarters are part of the same module.

2. A side by side module arrangement was adopted for
   a. providing two means of egrees with each added module,
   b. greater structural integrity,
   c. minimum atmospheric drag,
   d. improved utility interface and accessibility and
   e. differentiated IVA mobility (major and minor axis).

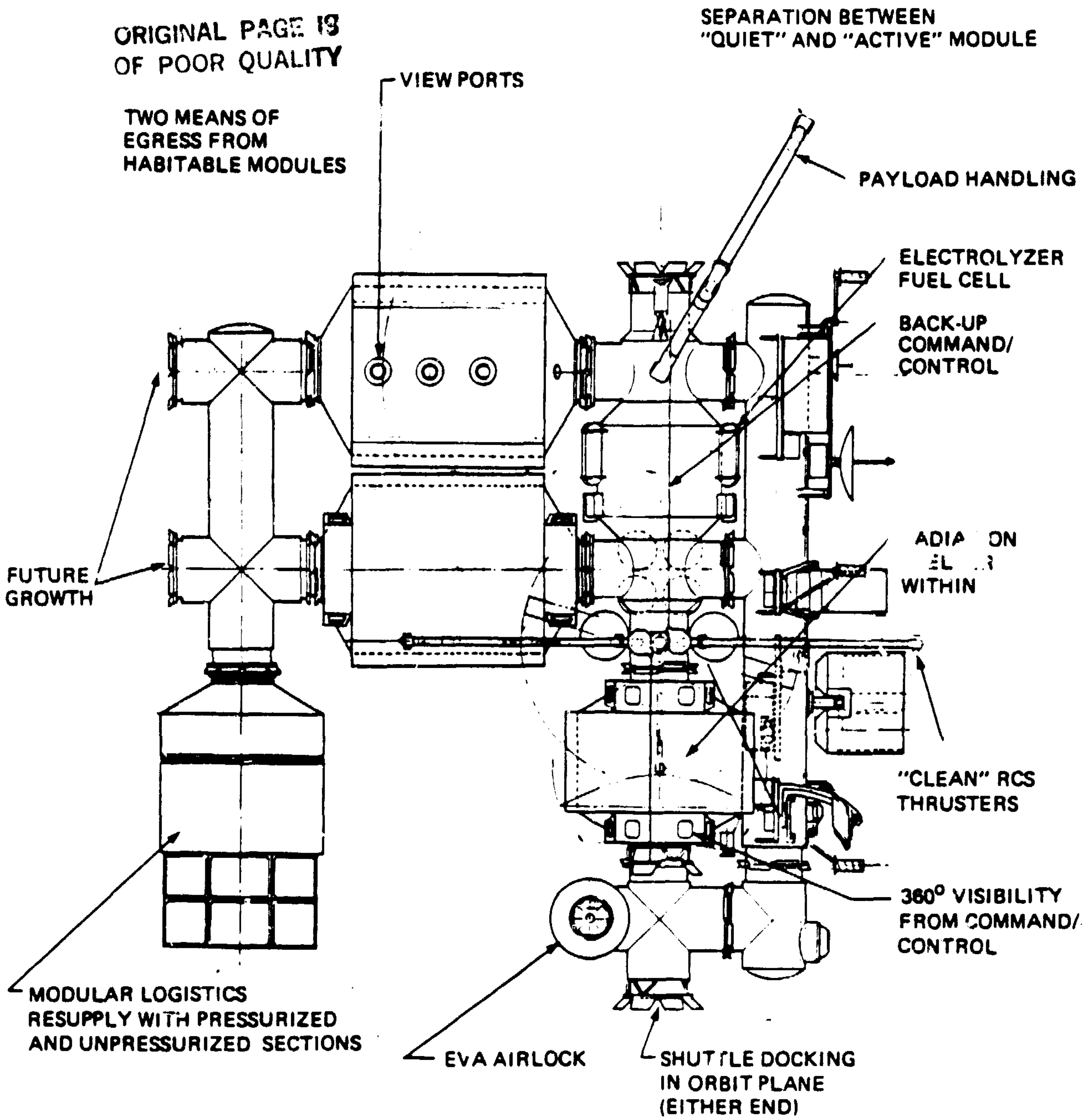


Figure 4.1-40 Attributes of the Incremental Space Station Architecture

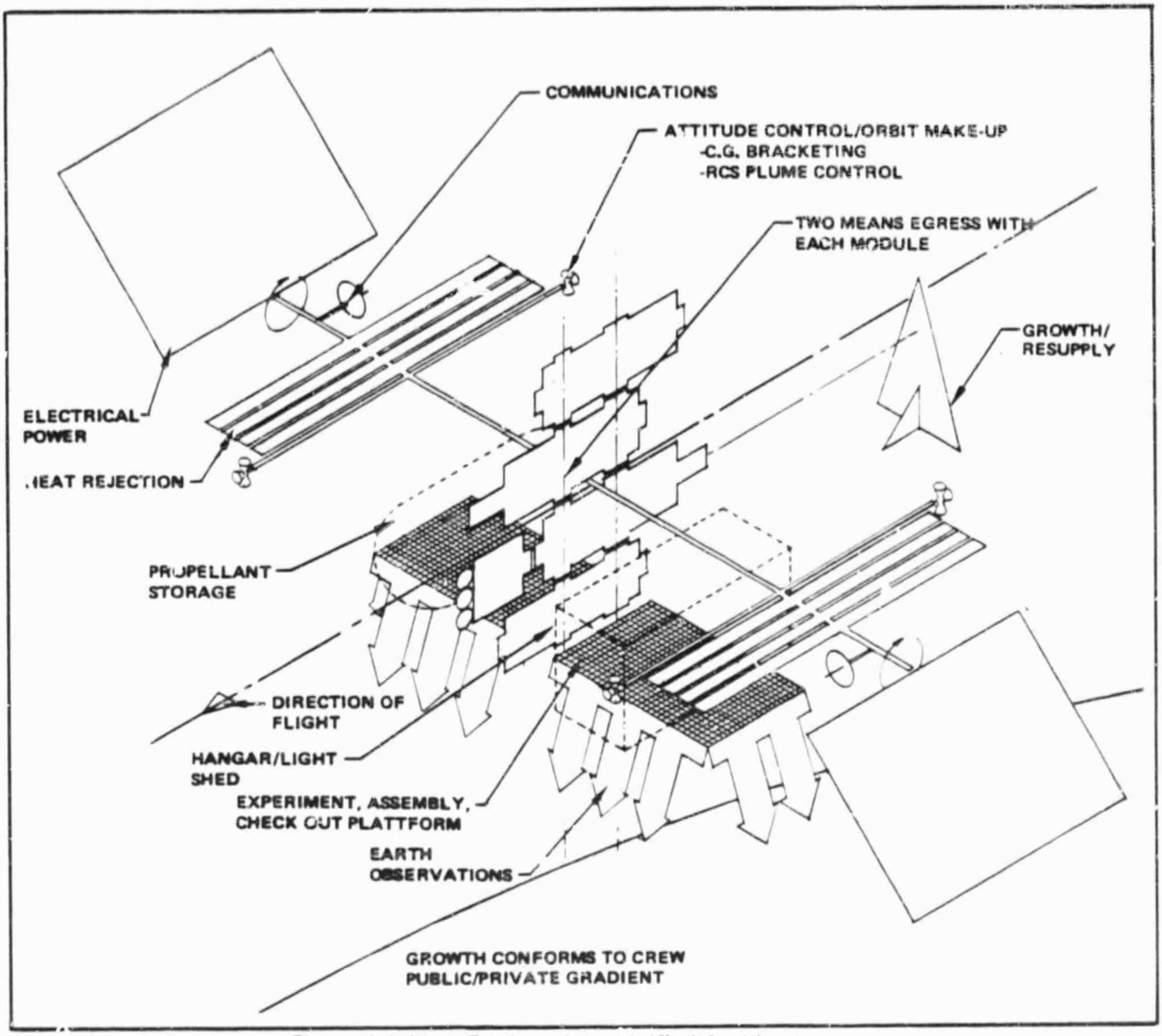


Figure 4.1-41 Zoning of the Unified Architecture

3. Command control functions in an analogous cockpit location with galley, dining, EVA suit storage sharing module space.

4. Growth pattern which extends the division of private and public domains without disturbing the initial arrangement. See Fig. 4.1-42.

5. Separate laboratory module with a integral multipurpose experiment, assembly frame in an earth oriented position.

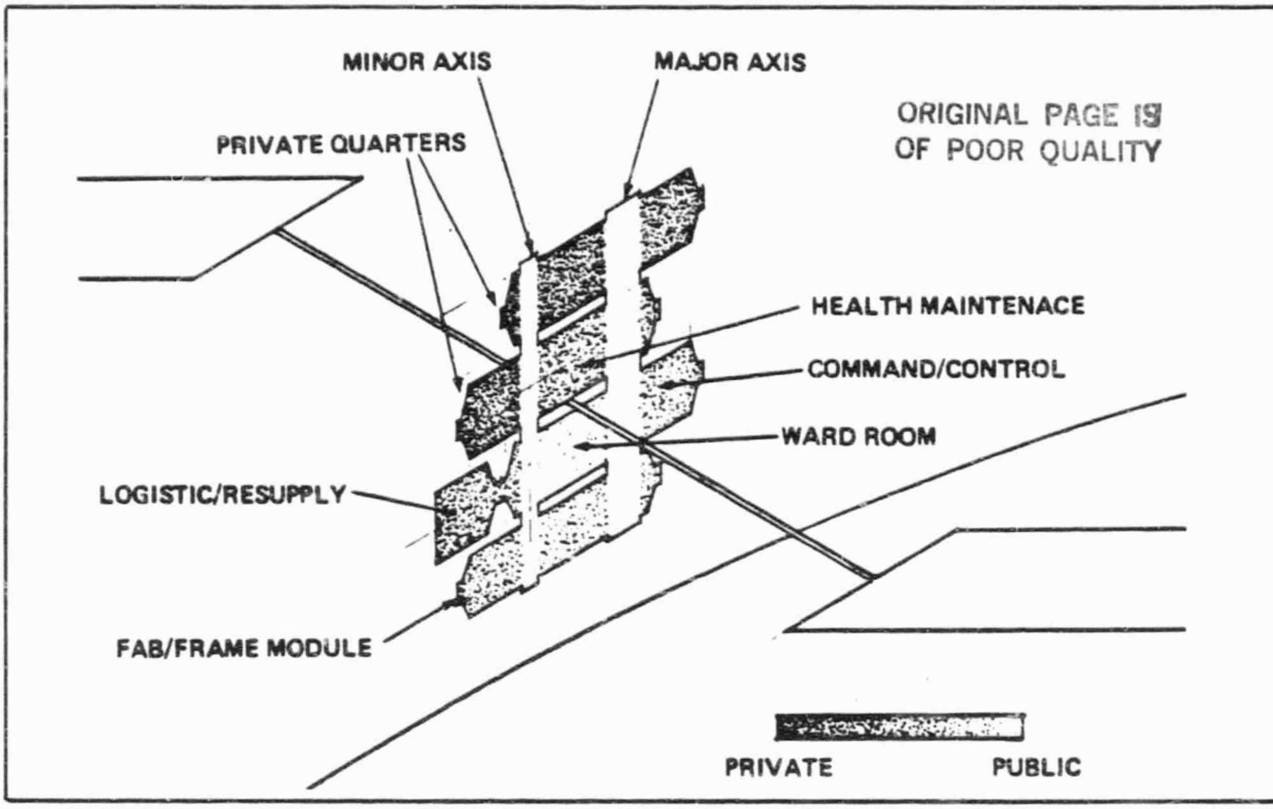


Figure 4.1-42 Internal Zoning of Privacy Gradient for the Unified Architecture

6. Growth which imposes the least controls penalty while meeting mission objectives.

7. Bracketing center of gravity to accommodate a range of mass distribution during build-up material and fluid transfer, varying mission operations and orbiter-attached configurations.

8. Array shadowing avoidance.

9. Plume impingement safe guards.

1.3.2.2 Elements

The sizing of the unified architecture modules. (See fig. 4.1-43)

1. Accommodates long length sections of deployable masts thus reducing the number of joints and increasing reliability and structural integrity.

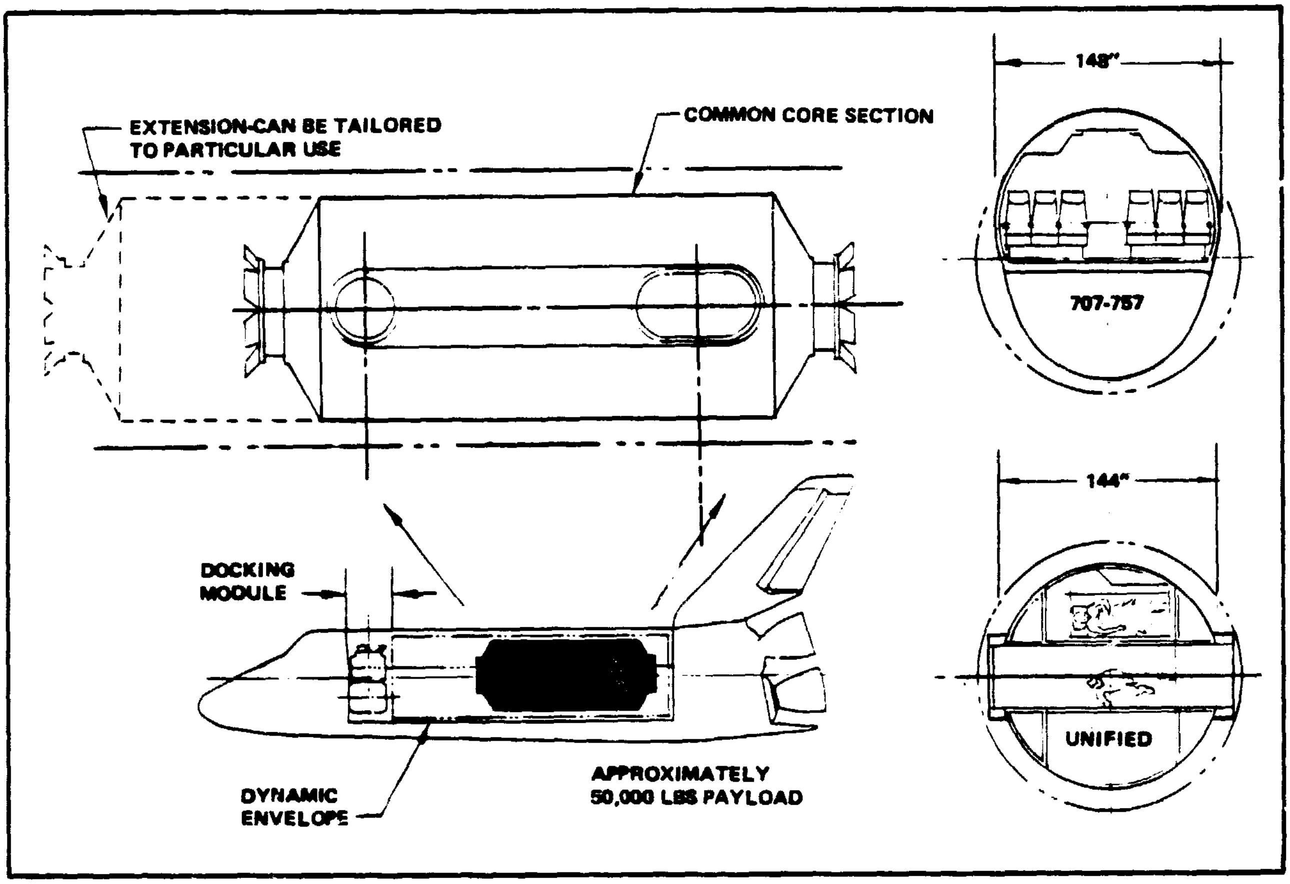


Figure 4.1-43 Sizing Rationale for the Unified Space Station Modules

2. Allows 360° visibility from a protruding command/control cab.

3. Offers a constant module diameter 4 inches less than the fuselage diameter of the 707, 727, 737, 757 aircrafts.

4. Has a module length which respects solar array packing sensitivity, orbiter airlock module in the cargo bay, on-orbit module arrangement and assembly clearance.

5. Sized for effective distribution of space station activities per module.

6. Provides a high degree of pressure vessel commonality. All habitable modules have identical pressure vessels excepting the laboratory module.

The overall unified architecture is shown in a composite form in figures 4.1-44, -45, -46. The major elements of the system include:

1. Crew quarters module - provides private crew accommodations, hygiene (hand wash, shower and toilet), health maintenance equipment, as well as, electrical power, attitude control, thermal control, communications, contingency command/control and EC/LS.
2. Command/Control - incorporates a zero-g "cockpit" for operations control, food storage, galley dining, EVA suit storage and reconditioning, air lock, ECLS, clothes washer and dryer and initial mission dedicated equipment. Figures 4.1-47, -48, -49 display the internal arrangement of both the crew quarters and command/control function within twin modules.
3. Laboratory module - is divided into two functions, one a shirt-sleeve lab and the other, an experiment mounting frame. The lab is designed to be flexible. It has provisions for 1) front loaded and supplied (elec., data, thermal) equipment, 2) an RMS mounted to the docking port, and 3) an observation section overlooking the experiment frame and earth. The frame supplies structure and umbilical stations (power, data, thermal, etc.) for experiments or satellite assembly and checkout. Furthermore, it provides the foundation on which both the future hangar/lightshed and propellant tanks are placed.
4. Crew quarters extension - responds to the demand of additional crewmembers by providing private crew quarters and associated hygiene support.
5. Logistics/Resupply - serves essentially the same function as in the incremental station that is, to replenish consumables and transport material up and down. Two versions particular to the unified architecture are shown in figure 4.1-50.
6. Hangar/lightshed - provides debris (meteoroid) protection, controlled lighting and an enclosure for satellite, teleoperated maneuvering system (TMS), orbital transfer vehicle (OTV) servicing, checkout, storage and launch.
7. Propellant tanks - on orbit storage of station, TMS and OTV propellants.

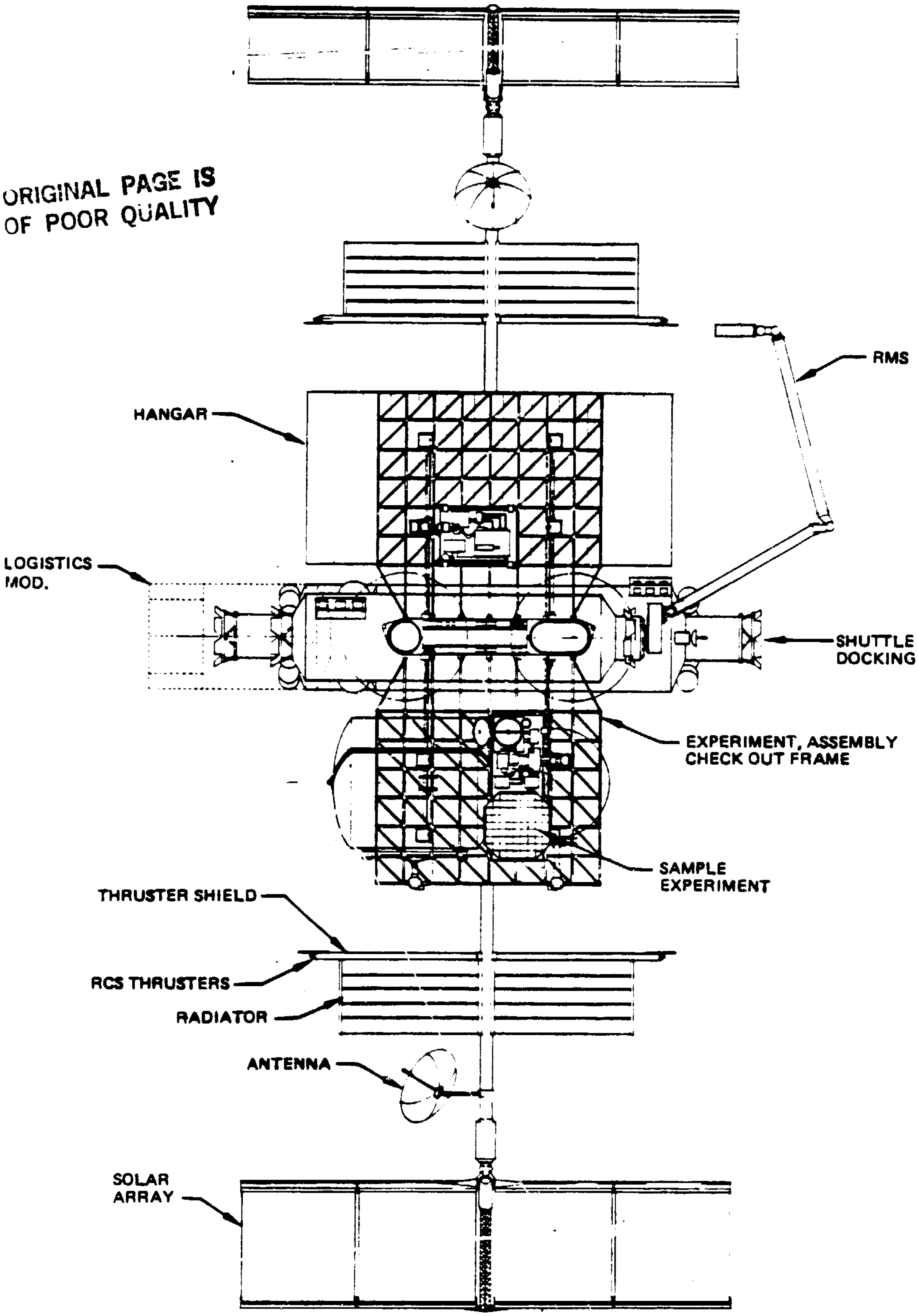


Figure 4.1-44 Earth Facing View of Unified Space Station

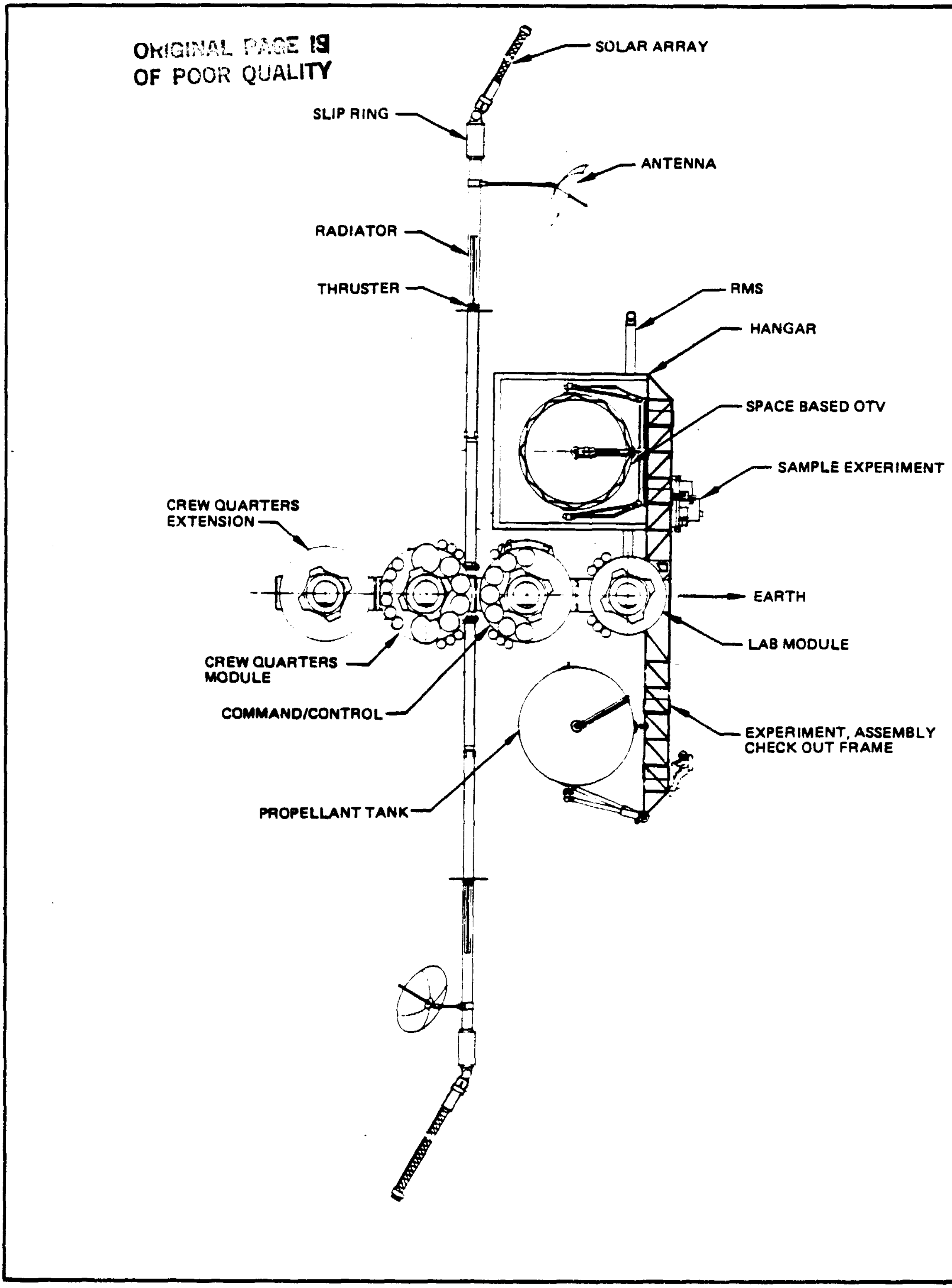


Figure 4.1-45 Unified Space Station, End View

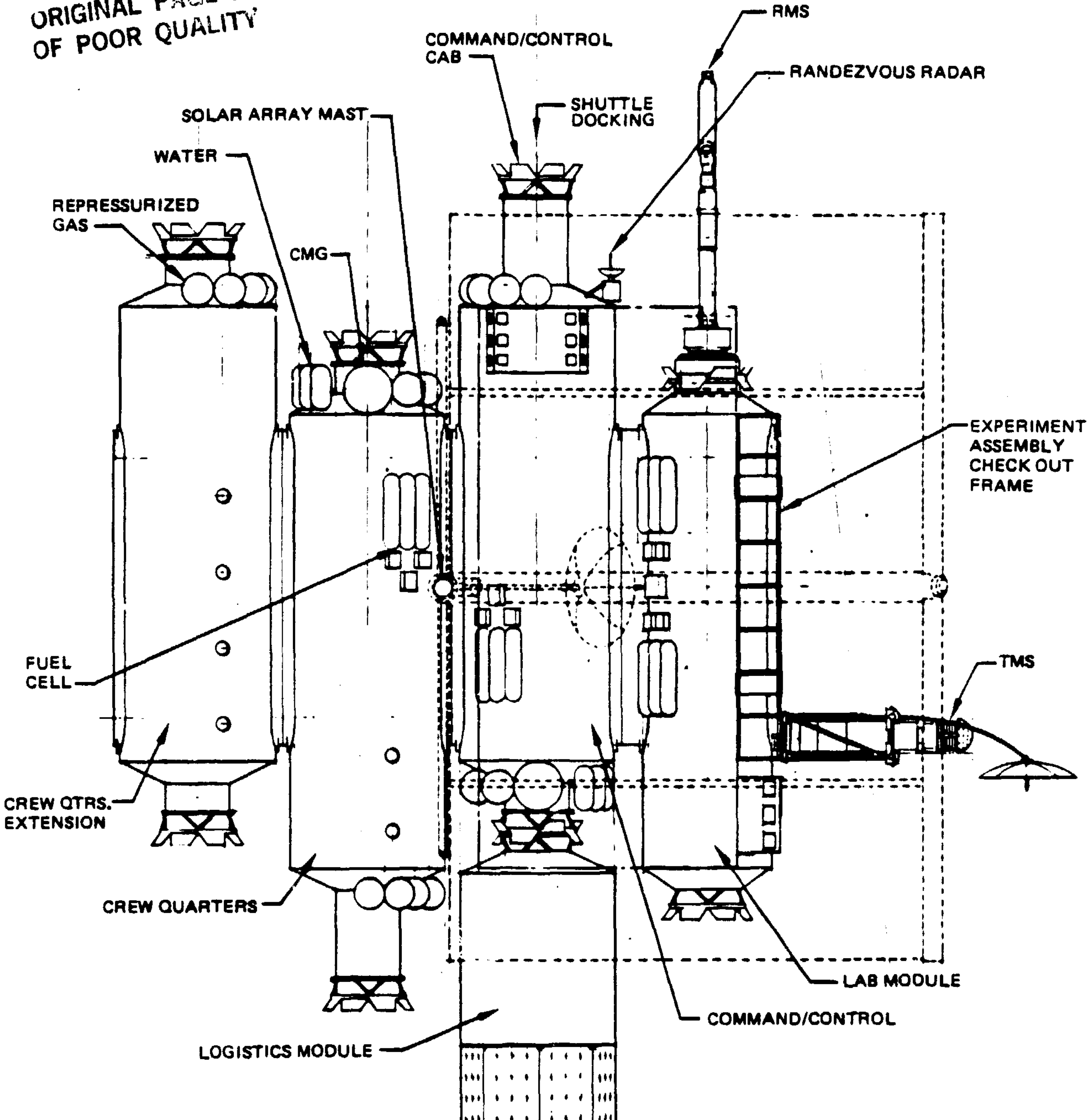


Figure 4.1-46 Unified Space Station, Plan View

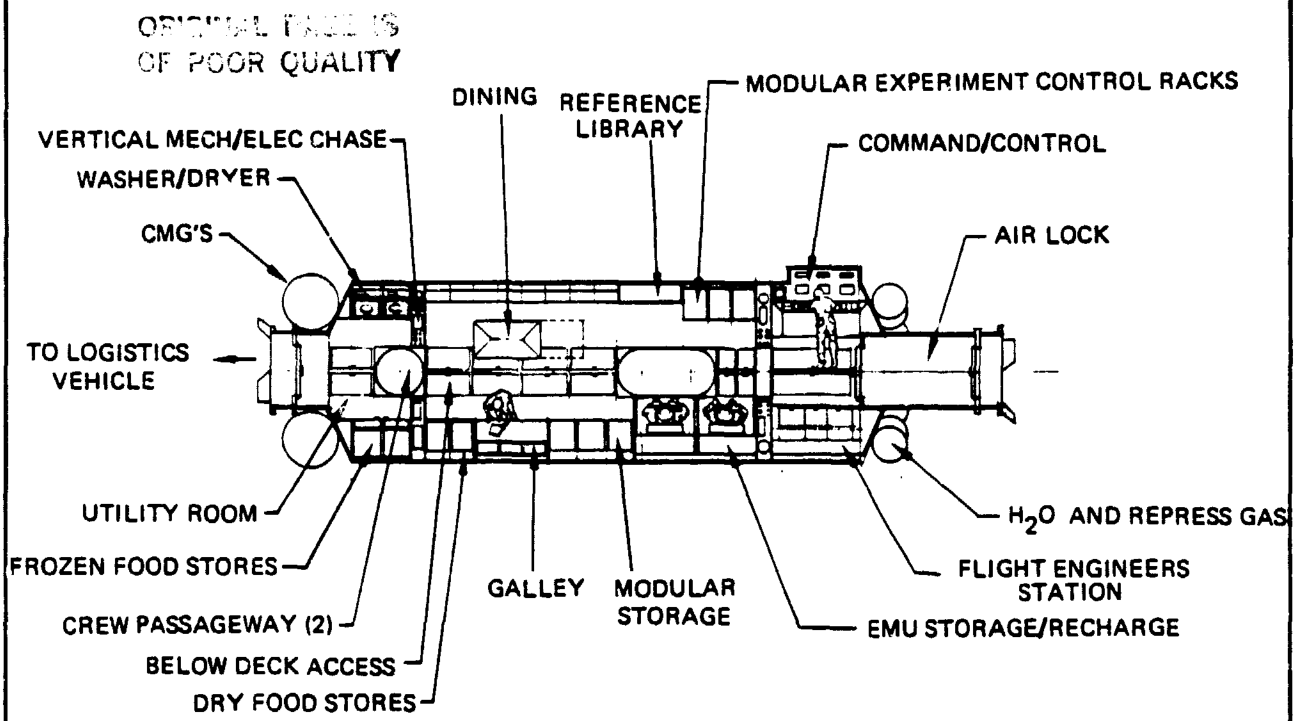


Figure 4.1-47 Unified Module Showing Command/Control Layout

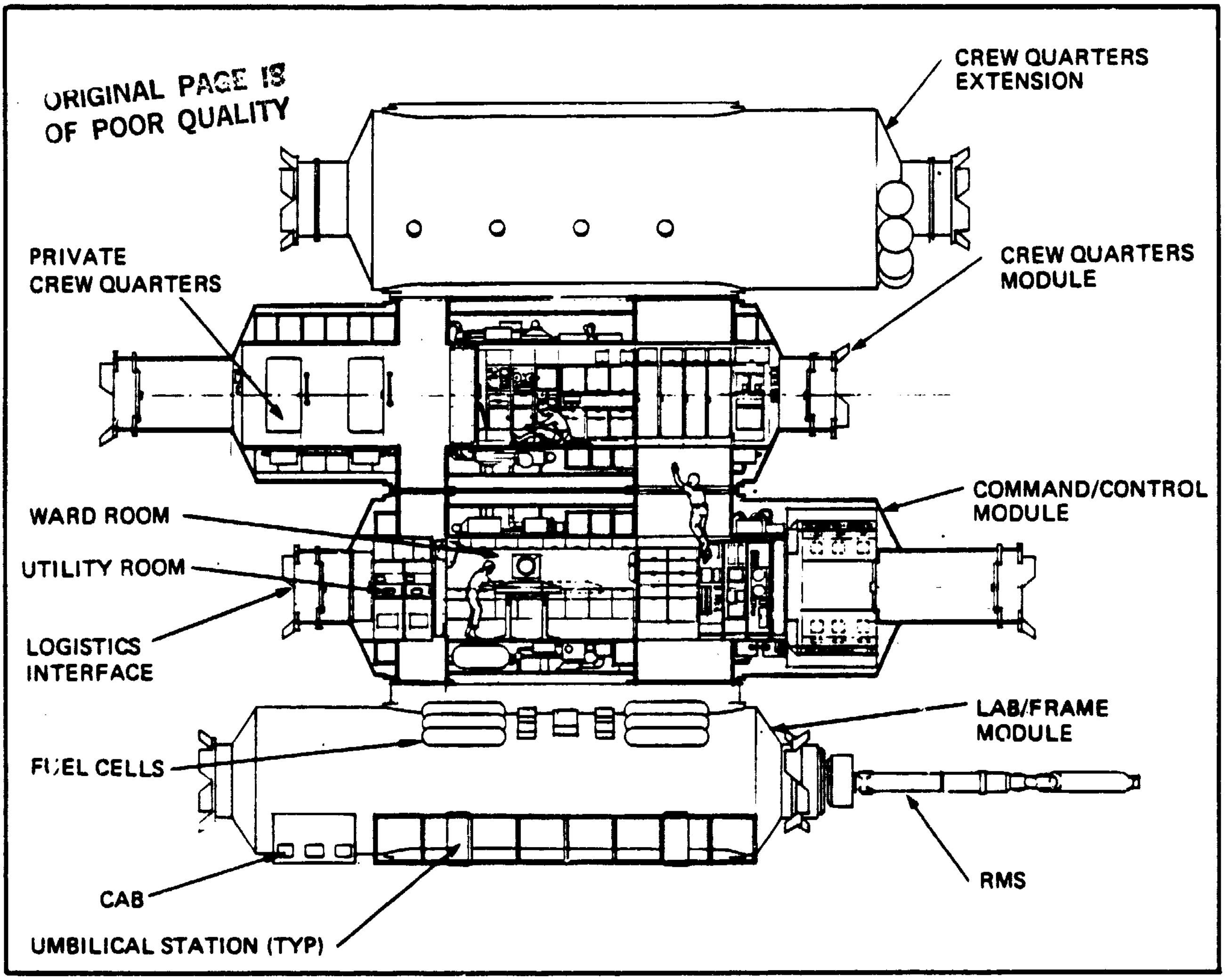


Figure 4.1-48 Internal Layout of Command/Control and Crew Quarters Modules

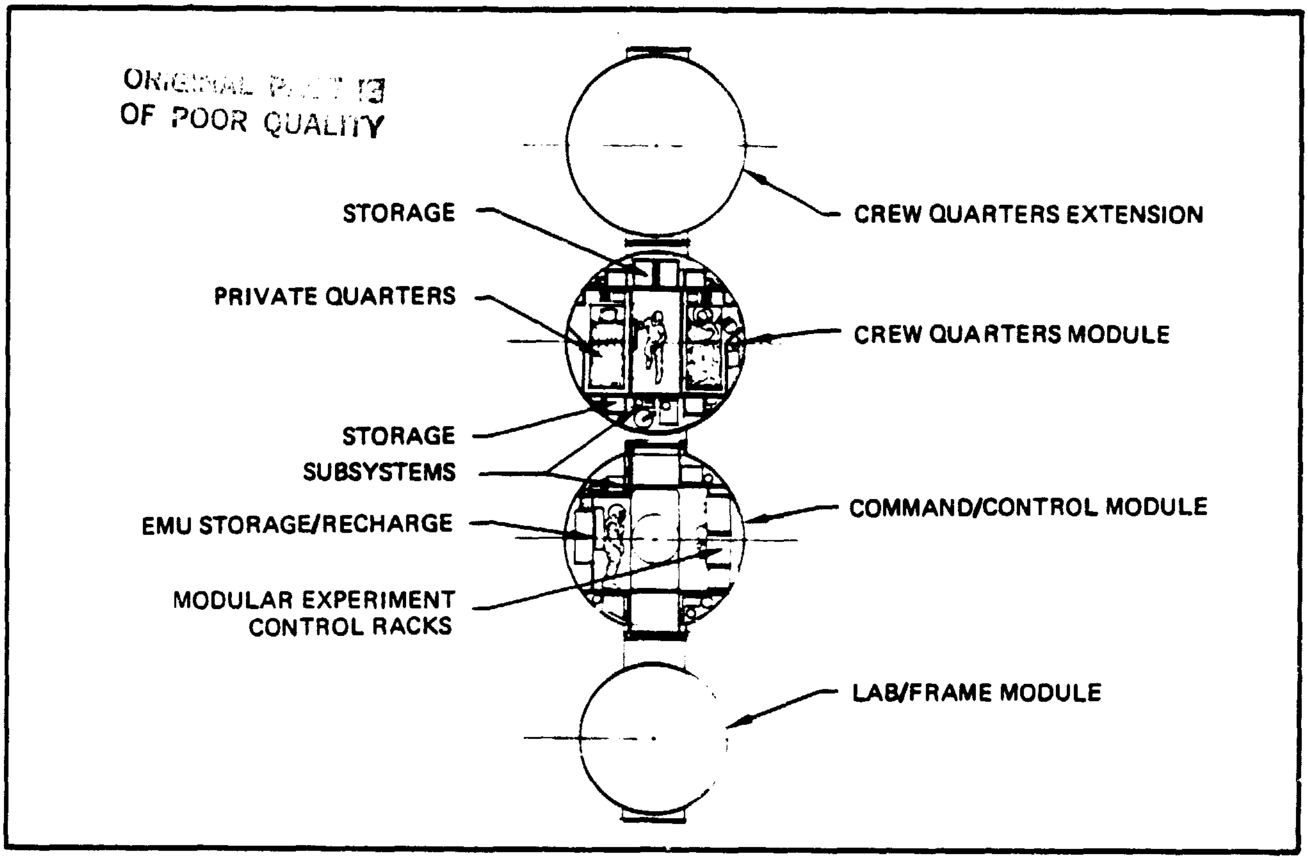
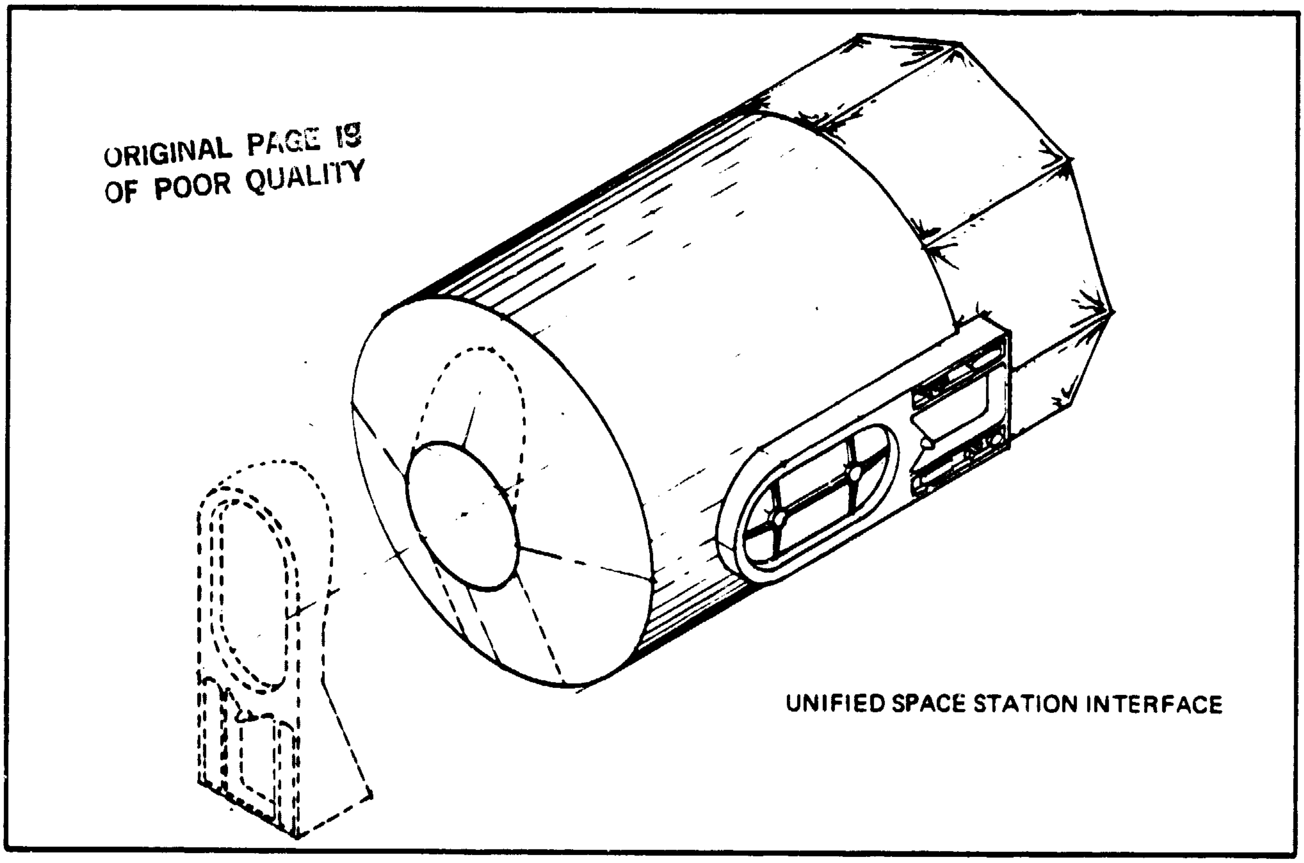


Figure 4.1-49 Transverse Section Throughout Unified Space Station



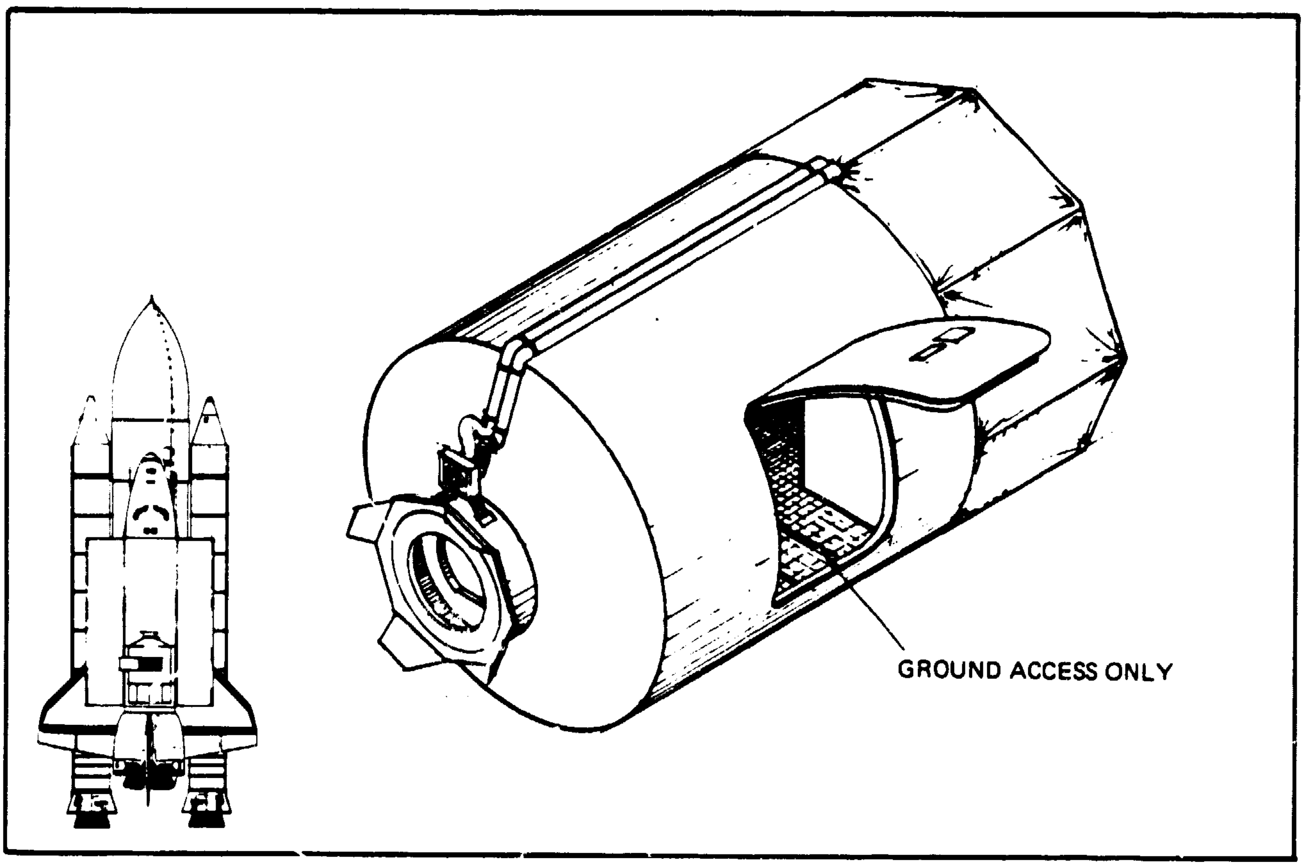


Figure 4.1-50 Logistics/Resupply Options for Unified Architecture

1.3.2.3 Growth

The build-up and evolutionary development of the unified space station is predicted on the following:

1. Anticipate areas of difficult growth (i.e., the rotary power transfer mechanism from array to station, and RCS location).

2. Allow for programmed growth (i.e., the enhanced performance of the EC/LS or other subsystems).

3. Form-fit demand on costly growth (i.e., solar cells).

4. Provide favorable orientations with respect to:
   a. earth observations
   b. shuttle rendezvous and docking
   c. solar array
   d. radiators
   e. antenna view angles

5. Grow in a manner that optimizes space station operations with respect to minimum atmospheric drag and minimum control penalty.

6. Maintain two means of egress with addition of each habitable module. The graphic representation of the evolutionary build-up is shown in Fig. 4.1-51 and is supported in the following description:

1st delivery - the first element placed in orbit is the crew module. This possesses all the requisite systems to maintain attitude control and maintain a ground control link. Since it is not occupied at this time, the sustenance EC/LS requirement is provided by the stations back-up system. Primary EC/LS functions are provided by the following command/control module.

2nd delivery - the berthing of crew quarters and command/control modules establishes the permanent space station unit.

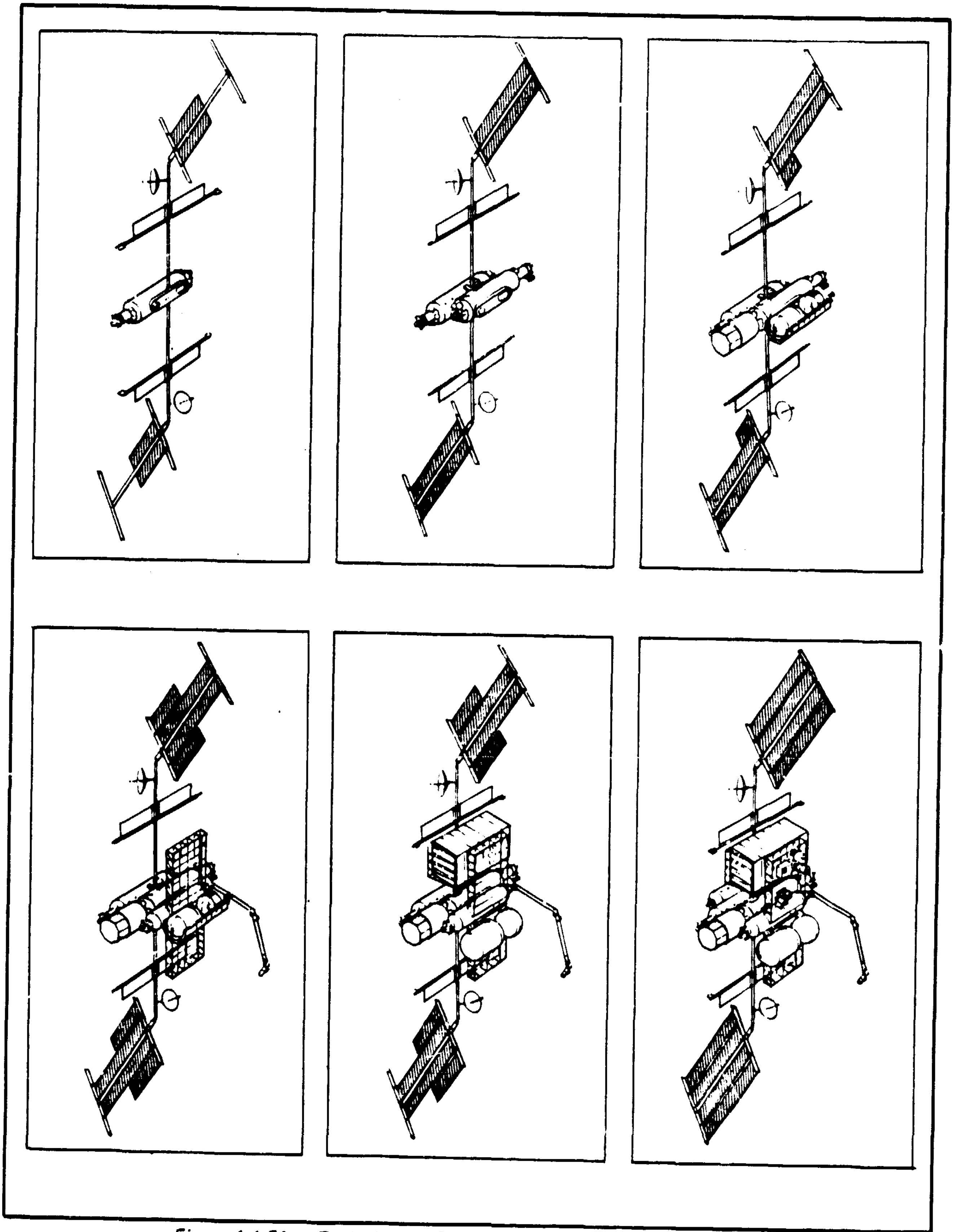


Figure 4.1-51 Evolutionary Growth of the Unified Architecture

3rd delivery - the next shuttle delivery brings a collection of both permanent and transient items. Included are 1) the logistics/resupply module which is attached as not to increase atmospheric drag and be efficiently located for internal use, 2) the teleoperated maneuvering system (TMS), used for satellite servicing and contingency space station orbit keeping, 3) small propellant tank for TMS resupply, and 4) the crew.

4th delivery - A laboratory module with attached platform is berthed to the command/control module, this addition meets the demand of internal lab space for commercial, science and applications missions, as well as, providing an earth oriented platform with umbilical interfaces for experiments, satellite assembly and checkout. A portable RMS is included in this delivery and attached to one of the module's docking ports.

5th delivery - further paced by demand, a hangar/lightshed is assembled on the "space" side of the existing structural frame. It provides controlled EVA workspace and storage for many purposes, however, is sized to accommodate a future orbital transfer vehicle. The location represents an attempt to position a transient mass as close to the ideal station center of gravity (c.g.). Furthermore, its orientation not only presents the minimum frontal area, but with the "draw bridge" doors open atmospheric drag is almost eliminated and an OTV launch platform is created.

6th delivery - trying to incur the minimum controls impact, propellant tank(s) are added to the station. It occupies an equal but opposite position to the hangar to balance masses, as well as, position its transient mass properties close to station c.g. and present minimum frontal area.

7th delivery - by this time, the workload requires additional crew members. The berthing of a crew quarters extension satisfies this demand and proportionally enlarges the station. That is, the private crew quarter and associated hygiene facilities are supplied in order that existing systems are not over-burdened. Also, the new modules' location is logical extension of the existing public/private gradient within the space station.

Further build-up includes a combined materials processing furnace and frame. The frame is essentially a mirror image of the existing and performs a similar task. That is, the "space" facing side accommodates experiments and provides heat rejection for the new furnaces. It also balances the station by producing a symmetrical configuration with the addition of hangar and propellant tank(s). Figure 4.1-52 shows a cutaway view of the unified space station.

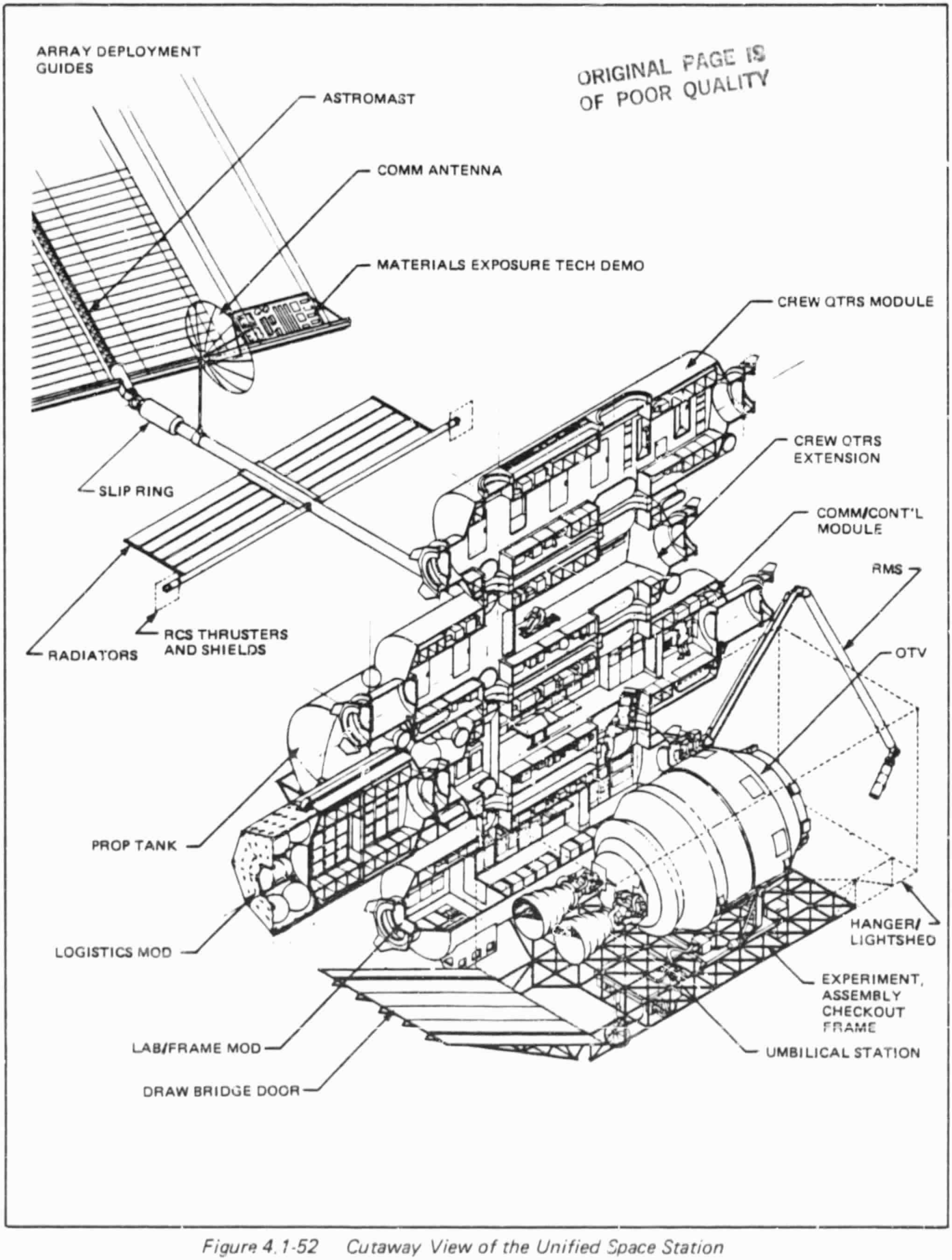


Figure 4.1-52 Cutaway View of the Unified Space Station

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1.3.2.4 **Attributes** (See fig. 4.1-53)

1. Compact "low profile" affords minimum drag
2. Two means of egress provided with berthing of each habitable module fig. 4.1-54
3. Excellent structural integrity fig 4.1-54
4. Excellent utility interface, access fig 4.1-54
5. Low contamination design
6. Efficient growth strategy options
7. Clearance for shuttle interaction
8. Integrated habitat/service module
9. Commonality (subsystems)

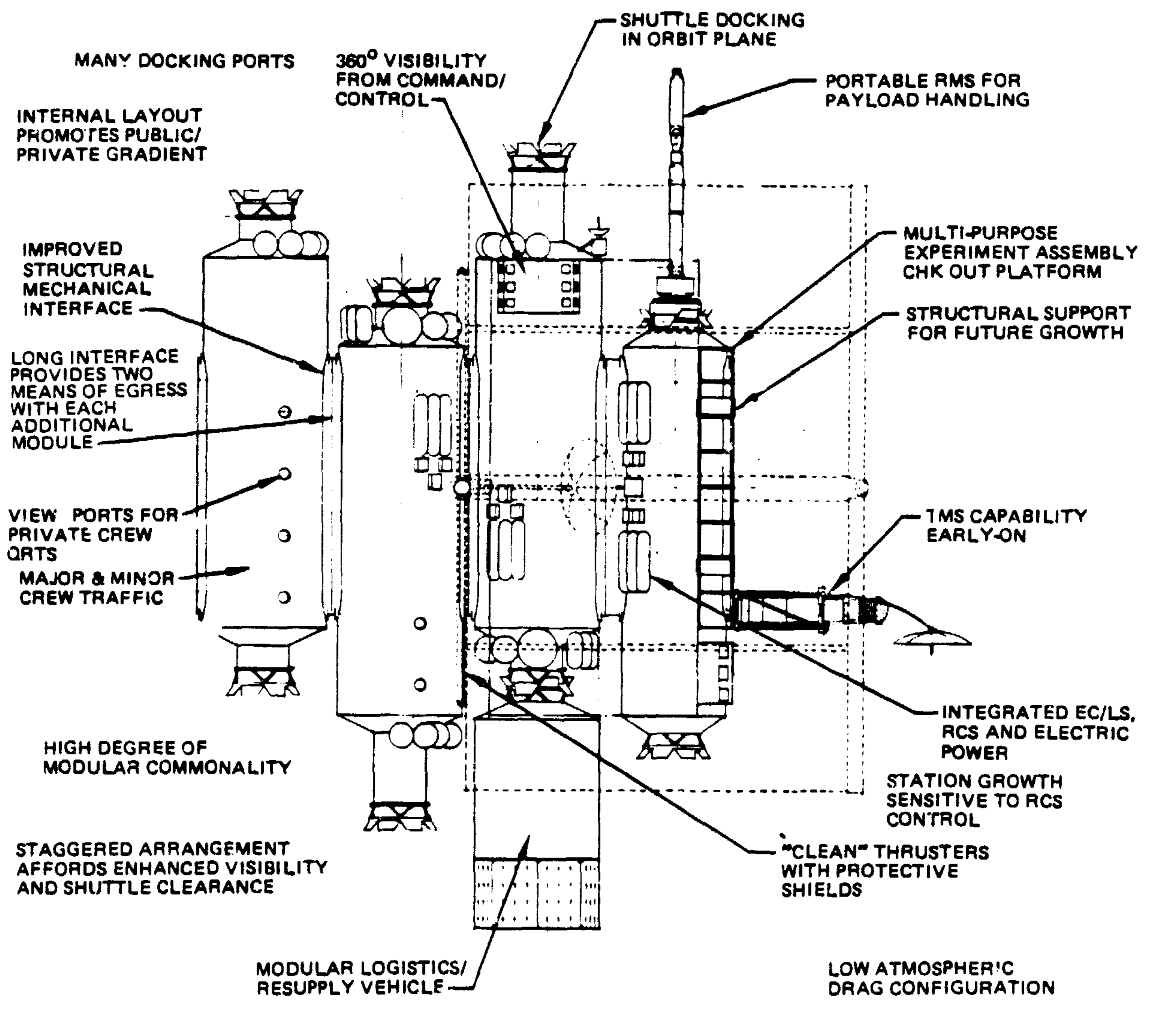

Figure 4.1-53 Attributes of the Unified Architecture

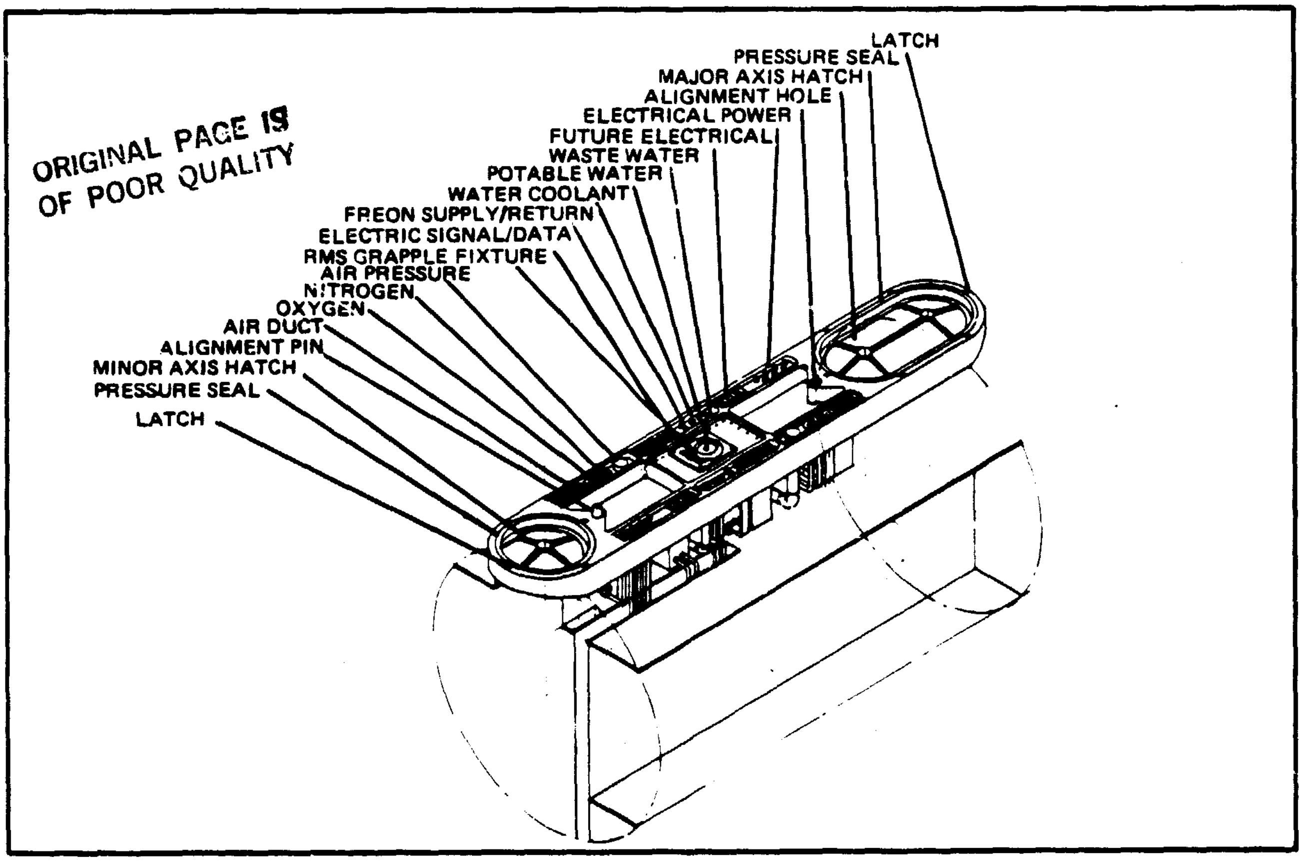

Figure 4.1-54 Unified Berthing Interface

10. Generous experiment accommodation
11. Adaptable layout
12. Major and minor axes for IVA mobility
13. Public/private gradient for internal planning

1.3.3 Derivative Architecture

1.3.3.1 Description/Objectives

A third architectural option is not a true alternative, but a derivation of the unified scheme. It differs, in that, the first delivery provides mission support in the form of an unmanned platform. Subsequent additions to the platform are a function of mission demand and funding requirements. Therefore, the platform can operate in its unmanned, shuttle-tended mode for an extended period of time or be mated to a manned module for crew involvement. It is important to note that our mission analysis work reveals considerable demand for crew involvement (six crewman) from the onset. To be sure, demand is not the only issue driving space station architecture and design. Consequently, this transitional approach was adopted and presents an alternate strategy of accommodating the myriad factors influencing space station design.

The zoning of the derivative architecture parallels that of the unified space station with the exception of the service functions which are assumed by the lab/frame module (see fig. 4.1-55). Some subsystems will also be relocated in response to an alternate build-up sequence and contingency provisions therein.

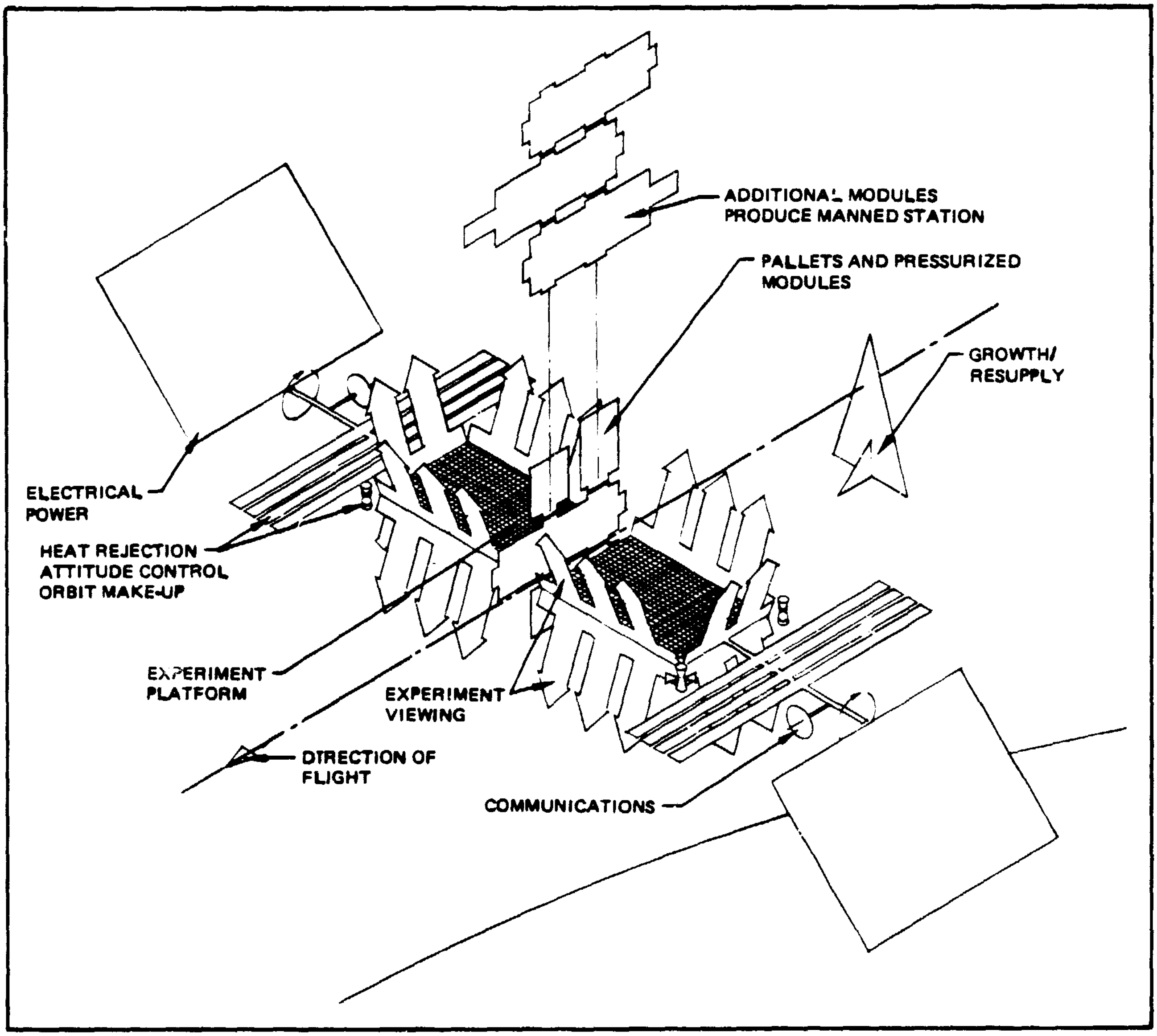

Figure 4.1-55 Zoning of the Derivative Architecture

1.3.3.2 Elements

The derivative space station is composed of basically unified architectural elements. As mentioned earlier, there is a modification to the lab/frame module to facilitate its unmanned operation. (See fig's 4.1-56 and 4.1-57)

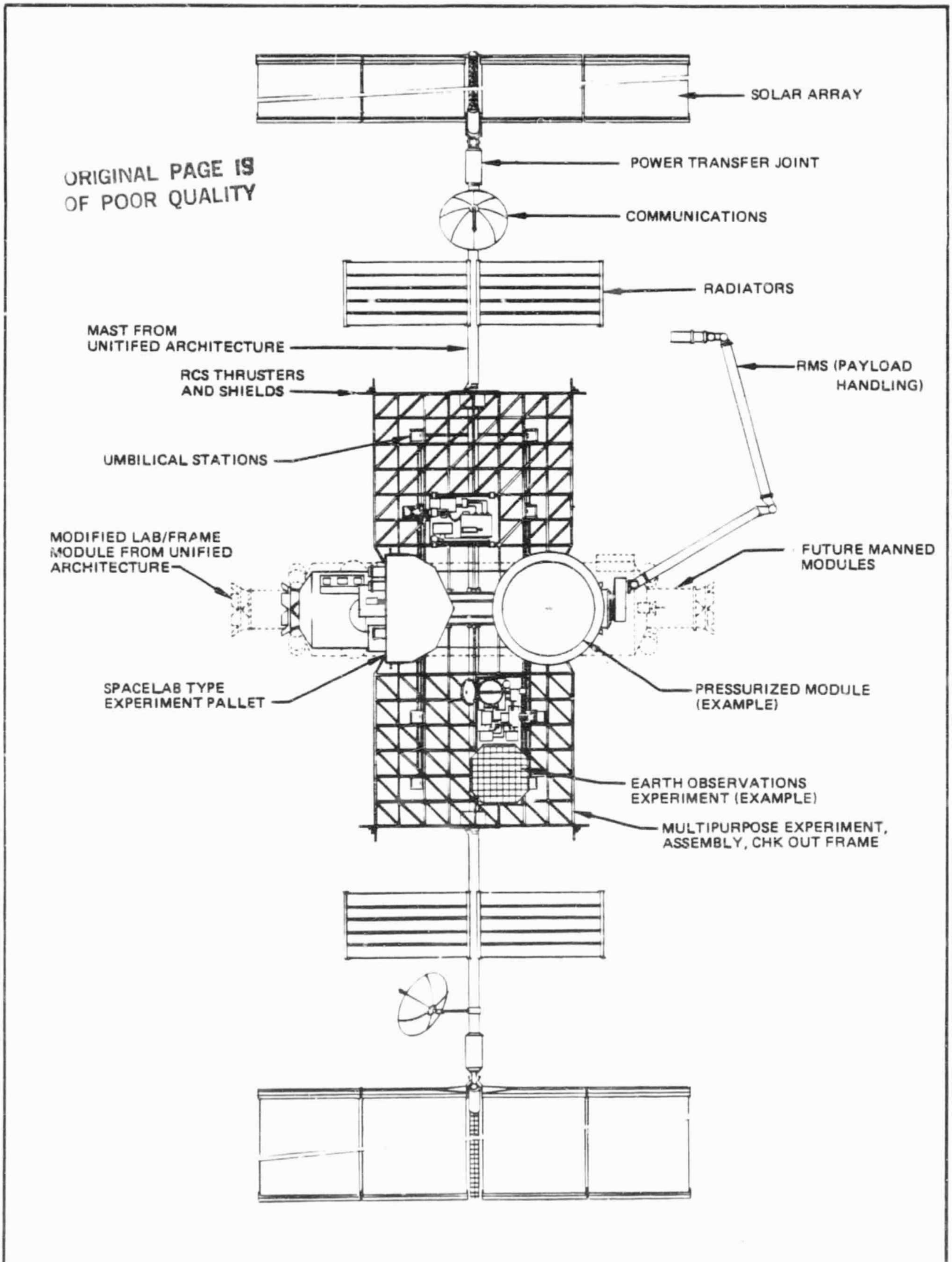

Figure 4.1-56 Earth Facing View of Derivative Space Station

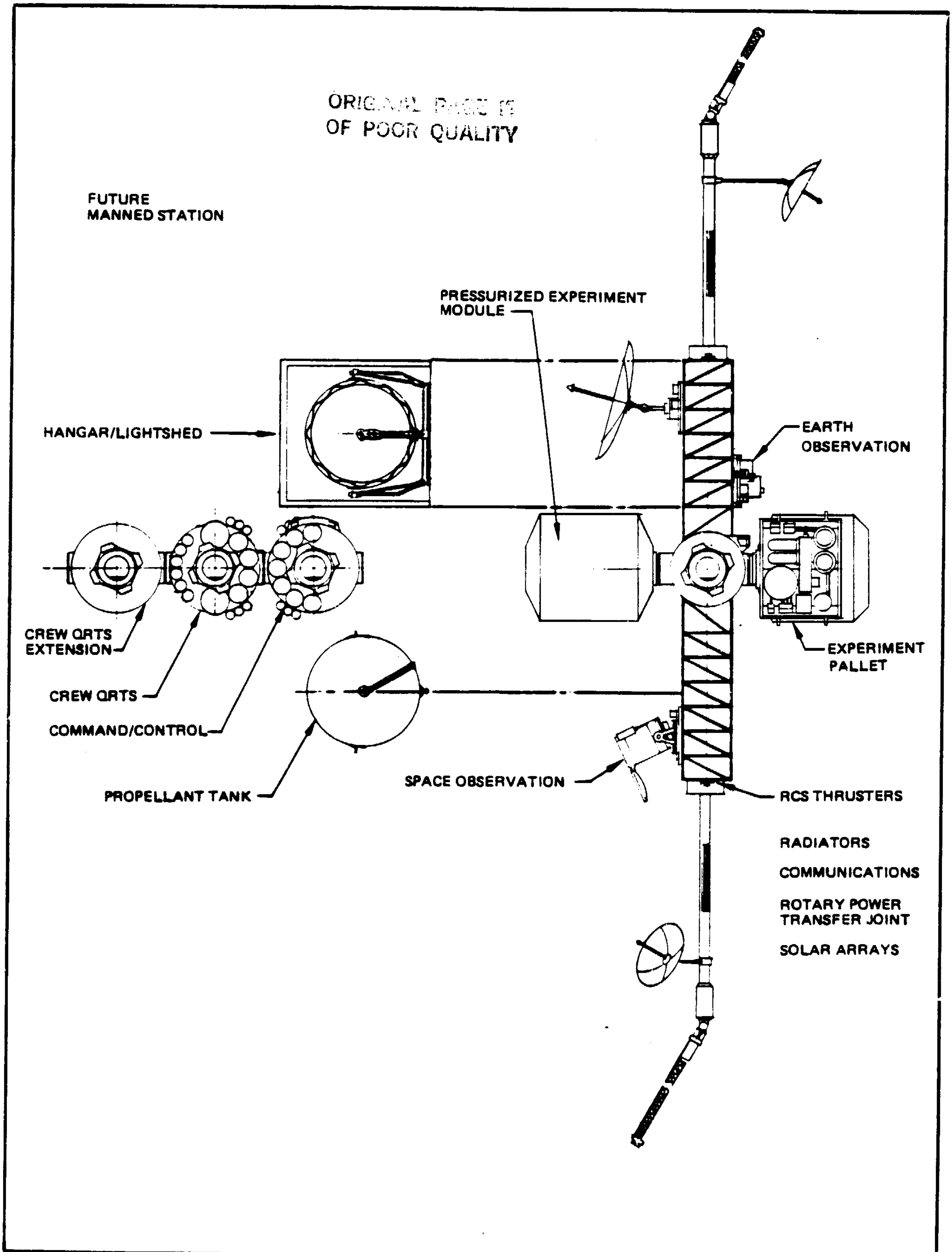

Figure 4.1-57 End View of Derivative Architecture

1.3.3.3 Growth

The factors which promoted a derivative architecture also pace its growth (see fig. 4.1-58). The initial delivery places a modified lab/frame module into a 500KM, 28½° orbit. From this point, the unmanned platform can provide commerical, science and applications support for an indefinite period of time. However, since the intent is to ultimately transition to a manned space station, the inclusion of anticipatory arrangements become an increasing burden or risk the longer left unused. When decided crew support is required, the command/control module is attached then the logistics/resupply module with TMS, small propellant tank and crew are delivered on the next shuttle flight. Subsequent build-up follows essentially the same logic as the unified evolutionary growth pattern.

1.3.3.4 Attributes

The derivative architecture possesses the following attributes: (See fig. 4.1-59)

1. Early unmanned platform opportunities
2. General purpose frame with umbilical service for experiment and satellite assembly/check-out support
3. Transitional growth to a manned station.

Attributes associated with unified scheme can be applied to the transitional architecture.

1.3.4 Comparative Mass Properties (See fig. 4.1-60)

As mentioned in 1.2.3.3: Level of Definition, one of the reasons for taking space station architectures to the conceptual design level is to test the implied capabilities by further defining the system elements and their integration. Since the distribution of activities is fundamental to space station operations, a reasonable level of resolution is required to validate packaging assumptions. In other words, can we get these capabilities in this module, fit it in the shuttle, and finally, get it into orbit?

This reasonable level of resolution is demonstrated in a mass properties comparison which shows the weight of the incremental service and command modules, as well as, the unified standard module. Therefore, at this stage of definition the assumed distribution of activities per module is within a conceptual design tolerance for the shuttle payload weight envelope.

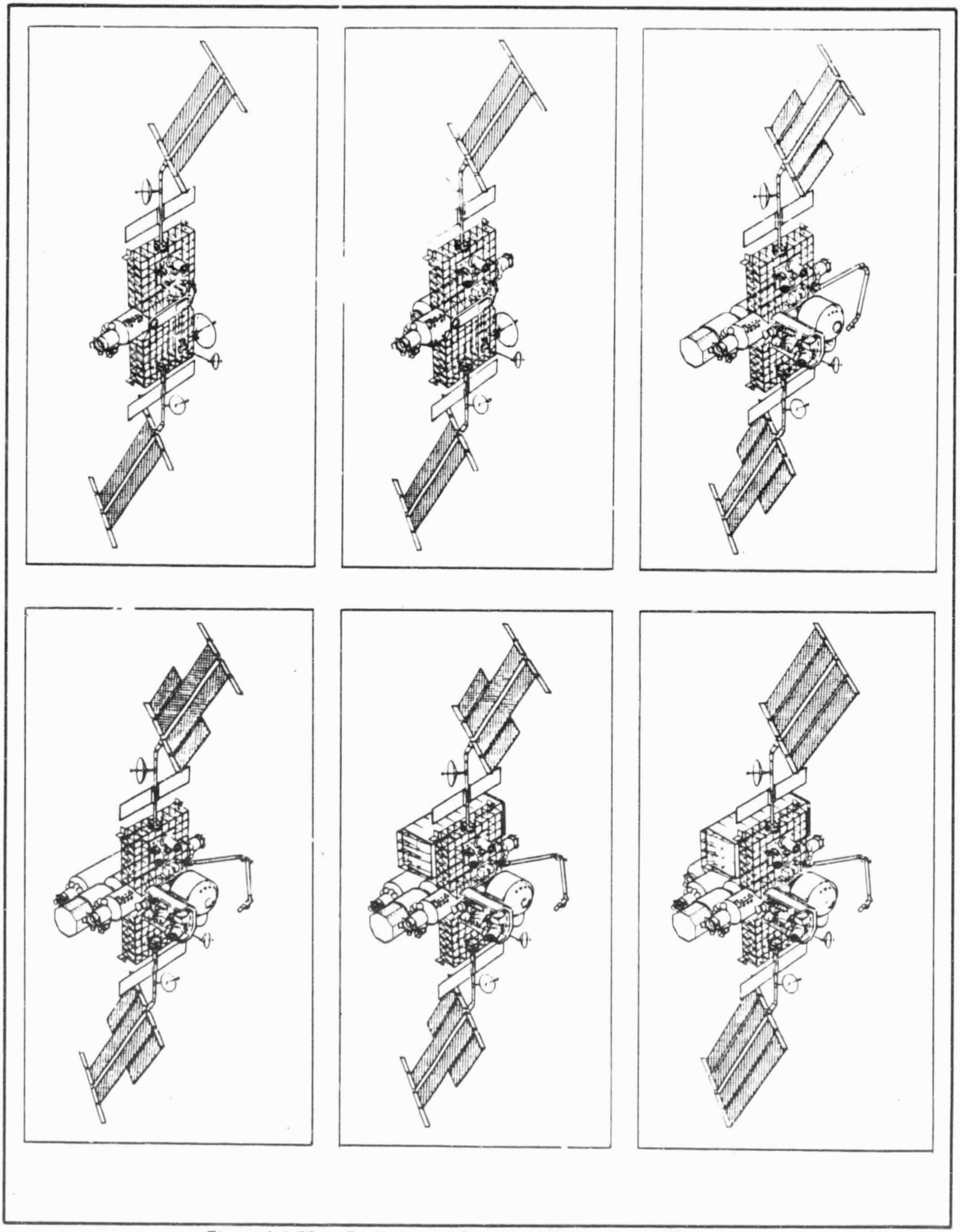

Figure 4.1-58 Evolutionary Growth of Derivative Architecture

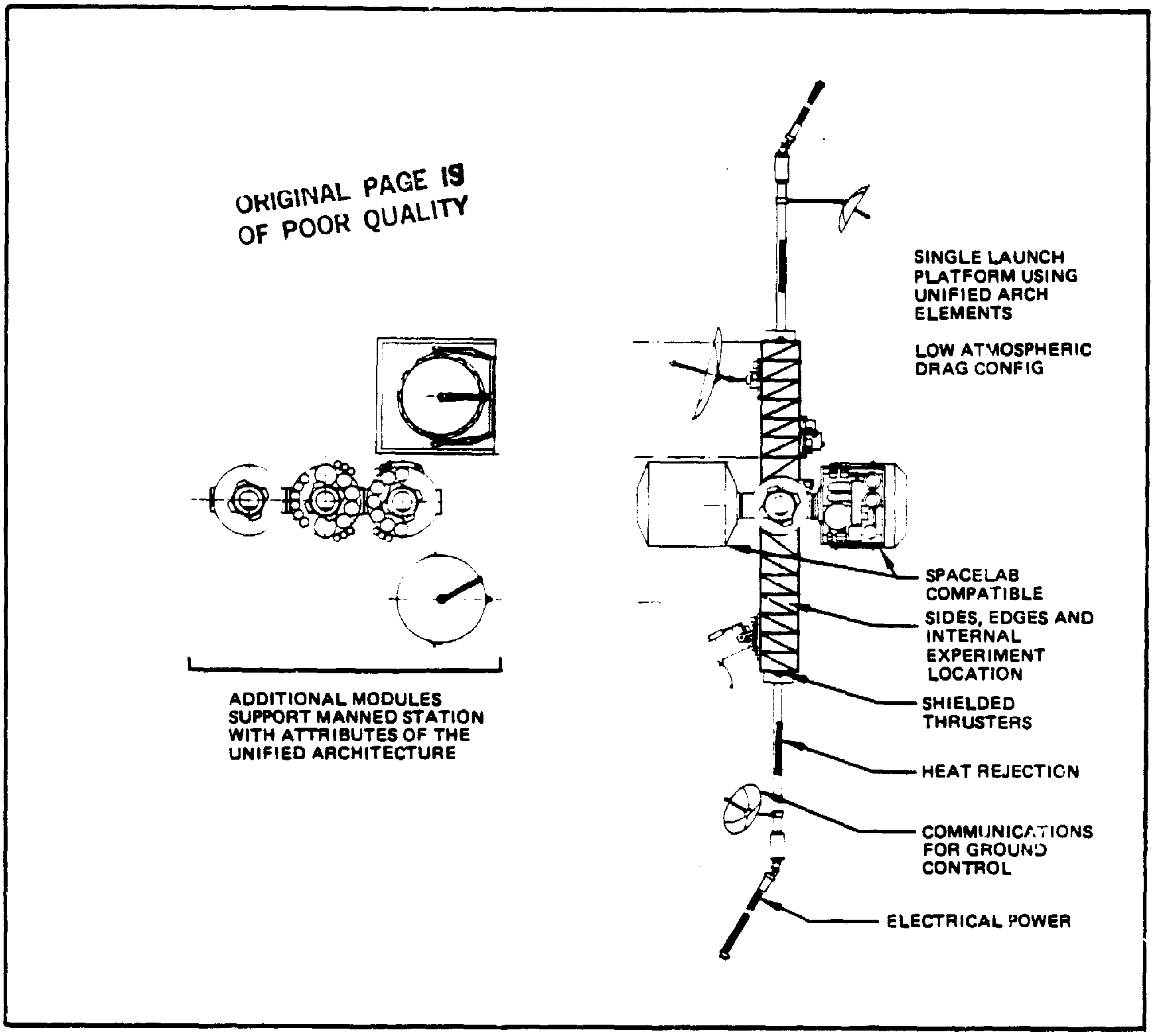

Figure 4.1-59 Attributes of Derivative Architecture

Item	Incremental Architecture				Unified Architecture	
	Service Module		Command Module		Standard Module	
	kg	lb	kg	lb	kg	lb
Structures	3562	7852	2981	6571	6798	14987
Cabin Shell	3104	6843	2142	4722	4236	9339
Other	458	1009	839	1849	2562	5648
Mechanisms	546	1203	164	361	408	899
Thermal Control	684	1507	831	1832	1364	3007
Auxiliary Prop	919	2026	0	0	587	1294
Ordnance	12	26	32	70	10	22
Electric Power	2609	5751	270	595	3478	7667
GN&C	720	1587	100	220	420	926
Tracking & Comm.	440	907	248	546	653	1440
Data Management	175	385	568	1252	481	1060
Instrumentation	100	220	36	79	100	220
Crew Accommodations	0	0	50	110	306	675
EC/LSS	829	1827	1475	3251	1911	4213
Mission Equipment	3026	6671	705	1554	1844	4065
Fixed	524	1155	73	160	100	220
Relocatable	2502	5516	632	1394	1744	3845
Growth	2690	5930	1522	3355	3854	8497
TOTAL	16312	35961	8982	19801	22214	48973

OPTION	AS WEIGHED	LOW INCLINATION		HIGH INCLINATION	
		CHANGES	MASS	CHANGES	MASS
INCREMENTAL					
SERVICE MODULE	35,961 LB	MOVE 5,000 LB MISSION EQUIPMENT TO CM	30,961 LB	DELETE M.E. LAUNCH W/O DM	30,961 LB
COMMAND MODULE	19,801 LB		24,801	DELETE M.E. ADD RADIATION SHELTER	31,000 LB *
STD 7-METER MODULE	24,500 LB *	LAUNCH 2 - ALL M.E. IN AFT	49,000 LB	LAUNCH 1	24,500 LB
UNIFIED	48,973	LAUNCH WITH HEAVY END AFT	48,973	NOT APPLICABLE	

* ROUGH ESTIMATE. DETAILED MASS ESTIMATE NOT PREPARED

Figure 4.1-60 Comparative Mass Properties

This is thine high reward:—the past shall rise;
Thou shalt behold the present; I will teach
The secrets of the future . . .
Below lay stretched the universe!
There, far as the remotest line
That bounds imagination's flight,
Countless and unending orbs
In mazy motion intermingled,
Yet still fulfilled immutably
Eternal Nature's law.
Above, below, around,
The circling systems formed
A wilderness of harmony;
Each with undeviating aim,
In eloquent silence, through the depths of space
Pursued its wondrous way.

SHELLEY
Queen Mab

1.4 SUMMARY

1. Methodology

   By itself, the approach does not yield space station architectures. However, it is instrumental in providing:

   a. a structured analytical format
   b. an inclusive approach which examined all options
   c. an educated and informed point of departure
   d. a check list for review of candidate schemes.

2. Architectures

   Within the open class of space station options shuttle external tank architectures were considered and determined not consistent with mission demands. In addition, it required extensive modification to produce a station of questionable utility and was therefore not adopted as an effective or economic means of satisfying forecast needs. Tethered alternatives also proved untenable since no significant advantage could outweigh the identified risks. However, this arrangement was retained as an experiment option similar to the proposed shuttle mission. Free flyers are seen as providing conditions otherwise unobtainable on a space station (micro gravity, contamination control, orientation, power, etc.). The connection with the space station is through servicing and status monitoring. Shuttle derived launch vehicles presented attractive capabilities yet were not in line with a

modest start and evolutionary growth strategy. This heavy lift potential should not be eliminated from long range planning or aggressive space utilization models.

The architectural options resulting from the limited c. s offer the most effective means of matching demand with design. The three basic architectures are each adaptable to high and low inclination orbits, albeit through different means. The incremental scheme provides modular integrity and is driven by the shuttle launch capabilities to a polar orbit. The unified and derivative space stations are principally derived from low inclination orbit needs and facilitate the polar condition as a designed-in modification. Each is taken to a representative conceptual design in order that architectural level assumptions could be confirmed. This means that designs have accounted for 1) shuttle dimensional and performance compatibility, 2) mission accommodations, 3) on-orbit operations, 4) evolutionary growth, 5) contingency operations and 6) alternate funding schedules.

To conclude, these architectures are methods which can satisfy a demonstrated mission demand within a safe, efficient and cost sensitive program.

SECTION II
HABITABILITY CONSIDERATIONS AND SUBSYSTEM ANALYSES

HABITABILITY CONSIDERATIONS AND SUBSYSTEM ANALYSES

1.0 INTRODUCTION

Section II of Volume 4 presents a summary of the tasks that were conducted to analyze the man-in-space aspects of a space station, and to further define selected subsystems that were either omitted from or not sufficiently covered in the Systems Analysis Space Operations Center Study conducted by Boeing for NASA-JSC. Updating of subsystems analyses is necessary in view of the evolving nature of space station definition currently taking place.

One of the major tasks reported in Section II is an in-depth analysis of man's role in space, and the factors of human habitability, organization, and behavior that must be considered in the design of a space station. These topics are discussed in 2.0. Habitability Considerations. Subsystem updates are included for Data Management 3.0, Communications and Tracking 4.0, Environmental Control and Life Support 5.0, Resupply Considerations 7.0, and Thermal Management 9.0. In addition to these subsystem updates, three new subjects were addressed. These incude the Manipulator Subsystem 6.0, the Pointing Subsystem 8.0, and a Discussion on Interface Standardization in 10.0.

The design drivers identified in the above tasks have been incorporated into the Requirements Study, Volume 3 of the final report series, and were used to analyze and define Architectural Options I as Section I of this volume.

2.0 HABITABILITY CONSIDERATIONS

2.1 INTRODUCTION

The Skylab, Salyut and Shuttle crews have repeatedly stressed the importance of the tasks they had to perform, the organization of the ground and Space Station crews, the living and working environment, and the equipment they had to use. The crew Tasks, Organization, Environment and Equipment (TOEE) are all major factors in crew productivity, effectiveness, safety, physical well being and morale. The importance of the TOEE factors increase dramatically as flight durations are lengthened from a few days to weeks and months. With flights of 30 days or more, seemingly minor TOEE problems can seriously impact a mission or even cause a mission abort.

This section summarizes, (a) the tasks for humans in space, (b) the organizational systems, (c) the space station environment, and (d) the equipment/human interfaces.

Much of the material for this section (para. 2.3.1 ff) was obtained from interviews by National Behavioral Systems (NBS) with Skylab and Shuttle astronauts, mission specialists, and other NASA personnel. This information was combined with material from NASA Skylab and Shuttle documentation and general bodies of human factors and architectural literature. The detailed report from NBS is included in Volume 7-4.

2.2 TASKS FOR HUMANS IN SPACE

It has been demonstrated repeatedly that human presence in space is essential for the successful accomplishment of a wide range of mission types. These mission types are described in 2.2.1. Humans can dramatically improve the effectiveness and reduce the costs of many other missions.

2.2.1 Historical Perspective

The importance of humans in space have been demonstrated by the U.S. Apollo, Skylab and Space Shuttle programs.

Apollo - The lunar rocks selected and collected by the astronauts led to radical changes in the conceptualization of the history of the solar system. The astronauts on Apollo 13 demonstrated their ability to troubleshoot, repair, and modify severely damaged systems in realtime. A series

of Apollo experiments on electrophoresis resulted in the isolation of kidney cells that produce the enzyme urokinuse (UK) from the cells that produce erythrpoietin.

Skylab - The astronauts saved the mission several times. They deployed jammed solar panels, erected various sun screens, and performed numer s other repair tasks which would not have been possible using automated systems.

Skylab astronauts performed micro-gravity experiments which yielded major advancements in understanding a variety of zero-g material processes.

The discovery of warm water eddies in cold water ocean currents, and the observations of the widely meandering Falklands current, demonstrated the potential value of humans in space for oceanography and fisherie

Space Shuttle - The early shuttle astronauts discovered previously unknown properties of high altitude lightning. They also conducted experiments that substantially advanced electrophoresis technology.

2.2.2 Unique Human Capabilities

Humans have a number of unique perceptual, intellectual and physical capabilities which are not likely to be duplicated by machines in the foreseeable future. A few of the ways these unique human capabilities can be used for future mission types are given below.

Vision - The human visual system exceeds film and video systems in sensitivity to (a) slight differences in color, (b) small contr . and (c) patterns and textures. The ability of the human visual system to accommodate wi ranges of color and contrast exceeds film and video systems. The agility of the human visual system to change sensing modes is unmatched by current, or planned film and video systems.

Humans using direct vision can scan large areas and then concentrate on areas of interest. Automated satellites often send back vast quantities of data that requires slow, difficult review (Viking sent back 75,000 reels of image data that was largely unused).

Humans learn over time to "see" or interpret visual displays or phenomena. The Soviets reported that it required them two months in orbit before they could "see" trains on earth. They also reported gradually acquiring the ability to detect ships, first in transit, then at port.

Physical capabilities - The human hand is the world's most versatile physical manipulator. No mechanical manipulator currently produced or under development comes close to the human hand and fingers in flexibility and degrees of freedom. The hand provides far better feedback of pressure, extension, heat and texture than the sensors available for mechanical manipulators.

Intellectual Capabilities - No machine system comes close to human reasoning and problem solving. Computers, now and in the foreseeable future, are not capable of solving ill-defined problems. Computers do not create new ideas, or develop new approaches to solving problems.

Humans can plan and carry out unique complex tasks in realtime. No machine can be programmed in realtime, in natural language, to carry out tasks that were not planned far in advance.

Improvements in computer hardware and software (especially the system user interface) will compliment and substantially enhance human intellect in space.

The human intellect comes equipped with the human visual system (the world's best) and the human hand (the world's most versatile manipulator) all in a very mobile unit (the human body).

2.2.3 Importance of Human Capabilities for Future Mission Types

Task requirements differ substantially between mission types. The importance of human capabilities will be discussed for each of the major future mission types.

2.2.3.1 Science and Applications

The major types of Science and Applications missions planned are (a) astrophysics, (b) earth and planetary observation, (c) environmental observations, and (d) life sciences.

Astrophysics - The Skylab astronauts were able to see substantially more detail in the Comet Kohoutek than was shown by film systems. Halley's comet, and other transient bodies, can be studied directly by the astronauts.

Astronauts could scan large areas of the sky for features of interest much faster than earth bound astronomers. The space telescope and other sensors could be directed to features detected by astronauts.

<u>Earth and Planetary Exploration</u> - The Soviets have discovered that the ocean waters are virtually transparent from certain orbital angles. Direct visual observation of submarine features can yield extremely valuable information about the ocean floor that is not available by other means.

<u>Environmental Observations</u> - Direct visual observations of the oceans from orbit have already resulted in substantial advances in understanding the earth's oceans. U.S. astronauts discovered cold-water eddies in warm water currents and thermal layers. Soviet cosmonauts have discovered localized color anomalies in the oceans. The cosmonauts have directed oceanographic research vessels to precise coordinates to investigate the color anomalies and other phenomena discovered from orbit.

Direct observation of weather systems and ocean currents can provide for better weather forecasting. Realtime observation of dangerous storms could provide more precise warnings to threatened areas. Aircraft and ship traffic could be directed away from fast moving storms.

Other episodic events such as volcanic eruptions could be studied from orbit.

<u>Life Sciences</u> - A major purpose of the study of life sciences in space is to determine the effects of long term space flight on humans. This requires humans in orbit as specimen for study. Some of the primary data collection techniques are self report and direct observation by highly trained professionals. In addition, many of the measurement instruments must be operated by properly trained technicians.

Other life sciences research involves using the convection free zero-g environment to isolate and study complex organic substances that cannot be isolated in one-g (e.g., distinct classes of human lymphocytes). Many of these substances may decompose rapidly after separation. Thus they could only be examined in detail by humans in space laboratories.

<u>Space Sciences</u> - Several different types of basic research that may be conducted in the space station are grouped together as space sciences. Plasma physics is an example of this type of research. The zero-g environment would allow scientists to view the properties of plasmas contained by visually transparent magnetic force fields. Scientists and technicians will be involved in an interactive matter with running an experiment, observing the processes, and making modifications for the next run.

<u>Materials Science</u> - Space materials processing science missions have two major purposes: (a) develop materials processing for commercial space production, and (b) advance basic science.

A major concern in developing commercial processes is the time required for development. Private enterprise is generally interested in scientific endeavors that hold promise of yielding profits within a few years.

In order to keep the development cycle for most space processes within acceptable time limits, each processed batch of materials must be quickly examined, and an adjusted batch be submitted immediately. More detailed examinations must be done as soon as feasible to further refine modifications to the process.

The examination of the processed materials, and preparation of the batches, can only be done very poorly, if at all, by remotely operated video and manipulators.

The people who are most knowledgeable about a process (principal investigators) often must conduct the examinations. Thus principal investigators will often need to stay at the space station during process development.

There will be ongoing basic and applied research in materials science. Some of the studies will be advanced research on materials either in commercial space production or under technology development. Other studies will be on materials or processes which at the time will not be serious contenders for commercial space processes. The research on processes in production may be radically different than non-production processes.

With production processes, the actual processing of the materials may be accomplished by sending a research batch of materials through an automated production system. Or the automated system may be reconfigured or reprogrammed for a research batch.

The research procedures for non-production processes may involve numerous experimental runs comprised of constantly changing complicated precision procedures. This type of research will be labor intensive and the labor will probably be by highly skilled researchers. The procedures may require man to either frequently reconfigure research equipment, or to reprogram automated research apparatus. The researchers may need to personally verify the settings of each piece of apparatus and to directly monitor or control the processes during an experimental run.

2.2.3.2 Commercial

The commercial missions identified to date include (a) earth and ocean observations, (b) communications, (c) materials processing, and (d) industrial services.

Earth and Ocean Observations - Astronauts have already reported numerous features that are not detectable in Landsat imagery. Direct observation from orbit can improve the estimates of grain and timber production.

Humans in orbit can direct fishing fleets to currents containing high concentrations of nutrients and fish. Information on current flow could also be used to direct ship traffic to reduce fuel consumption and time in-transit.

Materials Processing - The space based materials processing which appear to hold the most promise are electrophoresis, especially for pharmaceuticals, and crystal growth, in particular gallium arsencide crystals for semi-conductors. Both of these processes show promise of becoming large production operations requiring up to 30 shuttle flights per year just to transport materials to and from the space station.

The electrophoresis process will initially require human setup and monitoring of apparatus. Over time, the setup and monitoring procedures will become automated. Humans will be required for maintenance, repair and equipment modification.

Crystal growth will require the operation of high temperature electric furnaces. The batches of materials being processed in a furnace will be exchanged every four to ten days. Due to the temperatures involved, the batch exchange process may be automated even for initial production. Even if the batch exchange is done manually at first, it will be automated over time.

Both electrophoresis and crystal growth processes are driven by electric currents. The maintenance, repair and modification of the supporting electrical system may require human troubleshooting, workaround equipment repair and on the spot modifications. Humans on site will probably be required to insure that required production rates are maintained.

2.2.3.3 Technology Development

The technology development missions are transition states between basic science missions and commercial applications. As such they tend to be one of a kind and to involve extensive testing and evaluation. Generally they are not good candidates for automation, unless they are intended to specifically test automated systems.

The requirements for human involvement closely parallels the roles of humans in the science and applications missions.

2.2.3.4 Space Operations Missions

There are three major types of space operations missions: (a) space construction, (b) satellite servicing, and (c) flight support.

Space Construction - The space station will require on-orbit assembly and construction of large systems. The major pressurized modules will be delivered separately by the shuttle and joined on orbit. The unpressurized components will be packaged compactly for delivery and deployed or assembled in space. Humans will be required to operate the remote manipulator system (RMS) or other large manipulators that are used to connect the major sections of the Space Station. Some major sections of the Space Station such as storage and work platforms, and orbital transfer vehicle (OTV) hangars will need to be assembled by humans.

Other space structures, such as large precision optical devices, will need to be assembled and adjusted by humans. Assembled trusses can be stronger and more precisely aligned than deployed trusses.

Satellite Servicing - It is anticipated that humans will serve as mechanics and maintenance personnel to service, repair and modify satellites. The service and modification tasks may be automated in the near future. However, repair requirements will often be unpredictable and will require direct human vision, problem solving and manipulation.

Flight Support - Some of the servicing of OTVs will be designed for automated systems. However, damage due to unplanned types of contacts between OTVs, satellites and docking facilities may necessitate direct visual checkout and manual repair. Changeout of some avionics modules and the engines cannot be accomplished without hands-on intervention.

2.3 ORGANIZATIONAL SYSTEMS

The section, Organizational Systems, deals with the program structure, and crew relationships. This is a brief summary of a large data base of information collected by National Behavioral Systems. Volume 7-4 contains the complete report. However, the amount of data collected was far too great and detailed to include in this final report.

2.3.1 Program Structure

Autonomy - Support for autonomy is high, however, there is considerable concern about what autonomy "means" and what the costs and consequences may be. Crews would prefer to have "shopping lists" of activities which they manage day-by-day while the ground provides the general programming and goal setting.

Scheduling - Because of the larger crews, the complexity of operations and unanticipated occurrences, daily schedules would be optimally done by the crew on-board. The ground would provide "global" planning.

Mission Length - Astronauts expressed preferences for on-orbit stays of from 2 months to 6 months, with 3 months seen as optimum for early space station activities.

Workday Length - Crewmembers vary in their concept of the length of the work day - ranging from 8 to 16 hours. These figures tend to be imprecise because it is not clear if the hours include eating, exercise, breaks, etc. On long missions, however, there seems to be a consensus that crews need something near "normal" work schedules.

EVA Length - The length of the extra vehicular activity (EVA) will depend on the equipment available and the work to be done.

In addition to the particular mission, functions that affect time spent EVA are the time needed for donning and doffing the suit, assembly and transportation of equipment and tools to be used, and general "mental" preparation time needed to become acquainted with the work to be done.

Leisure Time - As missions become longer, leisure time becomes more important to crew morale and general well being. Crew members need time to prepare themselves for the day in the morning, some breaks from work during the day, and time to unwind and compose themselves for sleep at the end of the day. They also need a free day about once a week.

Some activities that would fall into this leisure time would be:

1. Looking out windows
2. Off-duty science
3. Talking to family and friends
4. Watching video tapes or movies
5. Using computers for games, word processing, etc.
6. Listening to music
7. Reading
8. Writing
9. Talking to other crew members
10. Painting or drawing
11. Ham radio, etc.

Shifts - Using shifts will depend on the work to be done and the general impact they would have on station activities, rest, etc. Crews are very concerned about adequate sleep and are concerned that shifts will interfere.

Exercise Time - Owing to the physiological changes in weightlessness, crew members will need to exercise at least 1 to 1-1/2 hours per day, six days a week. Since there will be limited equipment, it seems best to schedule the exercise times as part of the daily or weekly planning.

Sleep Time - Sleep requirements vary among people and as a result, crew members would like to have the freedom to determine their own sleep time and length. This suggests relative isolation within private crew quarters.

Job Rotation - In order to promote variety, backup, flexibility, interest, mutual understanding and mutual help, a program of cross training and job rotation is recommended. Although the scientists would probably spend the majority of their time on their experiments, a program which included them in the general housekeeping roster with duties related to operations that were commensurate with their skills would facilitate group interaction. At the same time, it would be recommended that crew members help with the scientific tasks when they were able to do so. Rigid division of labor is not recommended because of the separation it tends to generate among the members of the group.

Modular Scheduling - With the availability of computers, it would be easy to facilitate job rotation by setting up task modules that the crew would distribute among themselves as they

make up the daily and weekly work plan. Tasks are broken down into time units and identified for the skills required, making it easier for the crew to distribute tasks. This system would make it harder to develop "low status" groups among the crew and would foster smooth group functioning and interpersonal dynamics.

Authority - With the evolution of a space station, crew members think it important to make clear areas of responsibility for decisions, rules, obligations and duties. Two systems are preferred. One is the familiar military command system with one person in charge. The other is the chairperson system which divides responsibility among members of the crew with one person coordinating. Whatever system is to be used, crew members think it necessary to evaluate the advantages and disadvantages of each system and come to some position on the matter.

2.3.2 Role Relationships

The role relationships covered here are (a) internal, (b) external, and (c) training.

2.3.2.1 Internal

Sex Roles - Astronauts who have been on long flights, or who have had experience in isolated environments, see the mix of males and females on long missions as more a source of serious potential difficulty than crew members with shorter or no experience.

Antarctic experiences with mixed groups tend to confirm this concern with more problem groups than serene ones. However, there have been a few cases when mixed crews have gotten along well and with little difficulty related to sexual relationships.

This is an area which needs serious consideration.

Outsiders - Outsider refers to people who would fly on the Space Station for various lengths of time, but who are not NASA astronauts.

There is considerable difference of opinion among the crew and staff about the status these people should have, their degree of responsibility, and their status as members of the crew. This ranges from treating them as "guests" with minimal responsibilities, to "full fledged partners".

Crew members also vary greatly in their perception of "outsiders" as sources of potential difficulties because of either particular culture background or mission goals. Some see no problems while others would prefer to keep them on the ground with NASA crew members learning and performing their experiments in space.

Estimates of the time needed to train "outsiders" to fly safely ranged from 2-3 weeks to a year. A NASA study done by the Training Division estimates 150 hours over a 3 month period of time.

Scientists - There has been a historic distinction at NASA between scientists and pilots, and remnants of this still persist, and in some cases, carry over to "outsider" scientists. In long flights these divisions could be sources of tension if not dealt with early.

Military/Civilian - Current NASA astronauts come from either military or civilian backgrounds, each with a particular way of thinking. If these differences in perspective could not be resolved, they might be the source of major problems on long flights.

2.3.2.2 External

Family and Friends - Communication with family and friends is a very important issue with crew members. They would like real time communication links that are private and two-way television would be desirable. Crews would like to be able to initiate down links, but would like some ground filtering of uplinks.

Mission Control - Good rapport with Mission Control is very important to the effectiveness and morale of flight crews. Some of these transmissions should be made private and recording optional.

Two-way TV would facilitate this process as well as a shift of detailed scheduling from the ground to the station.

Career Path and Professional Growth

It is important that as space station activity grows, NASA develop a clear career, promotion and professional growth path for astronauts. Though not all would want management positions, these routes should be made clear, and options and requirements for growth defined.

2.3.2.3 Crew Selection and Training

Selection Procedures - There is a need to develop a means to evaluate crew personality traits for interpersonal dynamics on long term flights in order to aid in the development of specific flight teams.

Crew members must be team players and be dedicated to the overall success of the space station, even at the expense of their favorite projects. This will be especially critical in the selection of scientists and principle investigators (PIs) for space station duty. The PIs must have adequate understanding of the relative value of basic operations and other research to realize when other matters are more important than their favorite research. PIs must be willing to immediately interrupt, or even cancel, their own research, if their skills or equipment is needed to observe a different type of phenomena.

Crew members can have a strong influence on the on-board data reduction and selection of data for downlinking to ground. This data reduction and selection must be done in terms of what data is most valuable to the space station effort, not what is of prime interest to an individual PI.

Group Management Skills - Crew members generally see a need for learning group and conflict management skills for long duration missions in the confinement of a space station.

Ground Training - Training is necessary for efficient task completion in zero-gravity. Crew members report that tasks without training take 1-1/2 to 2 times as long with training. Even with training, it takes time to adjust to the weightless environment, starting slowly, step-by-step.

Mockups do not need all to be high fidelity for adequate training.

Onboard Training - Staying away from a system for a long period reduces familiarity and performance. Computer technology already exists for on-board simulation refreshers for: OTV, IUS, Fuel Transfer, Satellite Servicing, RMS, Shuttle docking/undocking, and moving cargo, as well as a means to improve and modify procedures and to learn new procedures.

2.3.2.4 Station Design Process

Crew Involvement - Crew members and staff definitely think that both groups should be involved in the Space Station design process from the earliest conceptual phases on through design development. Such inclusion will save money, enhance productivity, and eliminate much frustration for the flight crews.

Human Factors - Crew and staff would like to see human factors teams included in the design process from the very early phases in order to enhance crew productivity, effectiveness, morale, and mission success. These teams should have some authority and not be purely advisory.

2.4 SPACE STATION ENVIRONMENT

The environment addresses the general architecture and design of the station. The design of individual work stations is covered under Equipment/Human Interfaces (Section 2.5).

This section is divided into two subsections: (a) general environment, and (b) specific facilities.

Most of the data for this section was obtained from interviews with experienced NASA astronauts. The interviews were conducted by National Behavioral Systems under contract to Boeing in support of this study effort. A summary of the data obtained from those interviews is included in Volume 7-4.

These architecture and design factors have been integrated into the recommended Space Station System Requirements given in Volume 3 of this final report series.

2.4.1 General Environment

The architecture of a Space Station will be influential in crew productivity. Some of the major concerns deal with windows, separation of activities, interior orientation, color, ceiling heights, and private accommodations.

Windows - Windows are needed for numerous space station tasks including meteorology, oceanography, earth surveillance, astro observations, EVA monitoring, and docking operations. In addition, windows have a strong affect on personnel mental conditions. Experienced astronauts have stressed that windows should provide visibility in all directions. Windows should

be located in the living quarters as well as work areas. On Skylab and Shuttle, "looking out of windows" was one of the most frequent, and most enjoyed leisure activities. Earth observation during leisure time can accelerate the rate at which "space vision" is required. Thus, windows in the living areas can have a direct effect on productivity. Some windows should be large enough to allow several people to look out and discuss what they are viewing. The windows should be designed so that visibility does not deteriorate due to scratches, condensation or dust particles on the surfaces or between the window layers.

Interior Orientations - In zero-g, up, down, left and right are established by the current body position. Different rooms in the Space Station may have different up-down orientations. Even separate facilities or pieces of equipment within one room may have different up-down orientations. However, any displays, controls or pieces of equipment which are used together should have the same up-down orientation.

Color coding and directional indicators (arrows) should be used to help personnel to quickly, automatically orientate themselves relative to work stations or equipment. The same type of directional coding should be used in all work and leisure areas of the Space Station.

Color - The hue, brightness and saturation of colors are important for information displays and for mental condition. There is disagreement as to exactly what psychological modes are produced in the short run and over extended periods of time by specific colors. However, extended confinement to areas with only one very predominate color quite frequently leads to a strong aversion to that color.

The Space Station interior should contain a variety of hues. These hues should provide information about facility use and orientation to personnel. Observational work stations could be one color, and repair work stations could be another color. The colors in the living areas should be different than the colors in the work areas. (This helps to maximize the psychological separation of work and living areas).

Brightness and saturation on Earth are often associated with the up-down orientation. Darker and more saturated colors tend to be used close to the ground. Lighter and less saturated colors tend to be used above the ground. In the Space Station, a specific work station should have lighter, less saturated colors near the "top" of the station and darker, more saturated colors near the bottom.

Ceiling Heights - Generally, shorter "ceiling" heights are preferred in zero-g over conventional eight foot one-g ceilings. Also shorter ceiling heights allow crew members to obtain leverage

against ceiling equipment from foot restraints in the floor. However, shorter ceilings pose safety hazards during ground construction, testing and training. An effective ceiling height of six and a half to seven feet would probably work well for both ground and space use.

Separation of Activities - It is much easier for personnel to relax if they can get away from work areas and activities. This is especially true for two or three shift operations. The living quarters should be isolated visually and acoustically from the work areas. Ideally, the living quarters should be in separate modules from the work areas.

Noise and vibrations can travel through the structures of a Space Station. Certain types of activities (e.g., exercise) and equipment (e.g., compressors) create strong vibrations which interfere with quiet activities (e.g., sleeping, precision surveillance). The quiet activities need to be separated from the noisy activities temporarily (different times of day) and/or physically (different modules).

For two and three shift operations, it would be necessary to have separate living modules for noisy and quiet activities.

Acoustics - Sound waves were transmitted very poorly by the low pressure air system in Skylab. However, vibrations and noise traveled very well through the structure. Skylab had a lot of background noise from equipment and air ducts sending vibrations throughout the structure. Normal voice communications in Skylab were almost impossible at distances greater than a few feet. The intercom had to be used extensively for communications between crew members.

The mid-deck of the shuttle has noise background levels of 65-70 db. The air circulation fans, the treadmill exerciser and the waste control system are major noise generators. Shuttle crews have to use the intercom for voice communications.

Noise generating equipment in the Space Station should be acoustically isolated. Air ducts should be sized large enough to eliminate duct noise. Pumping systems should be sized and dampened to minimize vibrations. Quiet areas or modules should be acoustically isolated from noisy areas. Normal air pressure (14.7 psi) is recommended to enhance normal voice communications.

Decor - Skylab astronauts expressed the need for changeable decorations in a space station. Pictures, bulletin boards and posters should be movable. The color of lighting in living areas

should be changeable. Dimmer switches should be provided to adjust the lighting to activity and mood.

Television Systems - Good auditory and visual communications will make it much easier to achieve mission effectiveness. Modern TV and video cassette systems can greatly enhance the exchange of information on a real-time as well as a delayed basis. Operations, science and inflight maintennace and repairs will be greatly enhanced. Leisure activities that give the crew access to family and friends on a real time exchange basis and access to news, sports events, and movies, etc., via video cassette onboard recording will also facilitate morale. Color systems would be preferred.

Air-to-Ground Communications - All air-to-ground communication systems need some private links for mission management and conversations with principle investigators regarding proprietary experiments as well as conversations with family and friends.

Ground "dumping" of data should also be done so that the crew is aware of the activity in real-time, so they do not inadvertently spend a lot of time working with "dead" machines.

Contamination - There are five major areas of contamination:

The Waste Collection System
Food Spills
Trash
Exchanger Screens
Windows

Contamination of Skylab and Shuttle is thought to be kept low mainly because of the low humidity. However, nooks and crannies that are difficult to clean can become sources of odor as well as equipment which is not easily disassembled for frequent cleaning such as the washcloth wringer, parts of the waste collection system, and parts of exchanger screens that are difficult to access.

In order to cope with the steady accumulation of trash, temporary trash correction sites need to be placed conveniently throughout the spacecraft and disposed of daily by a trash compactor with wet or bacteria prone packages subjected to adequate disinfectants. Windows need to be easily cleaned.

2.4.2 Specific Facilities

To maintain high levels of alertness and efficiency, crew members need a place for good rest and adequate off-duty relaxation.

2.4.2.1 Private Quarters

Each crew member should have private, acoustically quiet quarters which permit sound sleep, room for off-duty activities while out of sleep restraint, writing, and adequate storage of personal belongings on a long term and temporary basis. Temperature, lighting, and airflow controls should be easily reachable from a sleep restraint. This room should also be equipped with electrical plugs for private stereo, video tapes, computers, or other uses. A window would be extremely desirable. The private quarters should be flexible enough to clean easily and to permit crew members the option of changing aspects of the color and decor to suit their tastes. Each room should provide for trash collection, and adequate body and equipment restraints.

Sleep Restraints - Crew members have widely differing preferences for sleep restraints. Crew quarters should be flexible enough to permit full restraint sleeping "bags" or simple attachments for those who like to more or less "float freely".

2.4.2.2 Wardroom

Since the wardroom will be a major off-duty area, it would be best to have it kept distinct from the galley, eating areas, work areas, and sleeping areas. The wardroom should be large enough for all the members of the crew to assemble at one time together comfortably, and should include areas for writing, temporary stowage, a large screen for video or movies, a video cassette machine, computer terminal displays and games. This room should be easily cleaned and the decor or colors pleasant and changeable. A large window would be very desirable.

2.4.2.3 Galley and Dining Area

While eating, crew members should have easy access to food and accommodations. No one should have to float over the table to get in or out, or access facilities. Floors and ceilings should be easily cleanable with adequate trash disposal near each crew member. The dining table should not be designated for any activities other than eating.

2.4.2.4 Personal Hygiene

Waste Management - Waste collection devices need to be private, easily and quickly used, and cleaned, with provisions for adequate restraints. The system should be designed to minimize lingering odors. Adequate lighting is needed for cleaning as well as reading. There should be provisions for temporary stowage, trash disposal, thermal control, and hand washing after use.

Shower - The crew shower should be quick and easy to use and clean up. Crew members would prefer hot and cold running water, a mixer valve, an airflow system to remove water, easy washing of hair and scalp, and a heated dressing area.

Exercise Equipment - Crew members need to exercise each day for an hour and a half or more. This can be done on a treadmill or bicycle ergometer. Efforts should be made to eliminate intense boredom from this activity as well as discomfort.

The exercise equipment should be designed and located so that crew members may look out a window, watch video, connect-up to audio systems, read, or carry on conversations while exercising.

Heat from exercising should be dissipated quickly to reduce the discomfort and hazard of overheating.

2.4.2.5 Food

In longer flights, food becomes an important factor in the quality of life. It needs to be appetizing, easy to prepare, and easy to clean up. There should be ample variety, pantry type storage, and free access by the crew for snacks, as well as some group meal times.

Crew members prefer frozen and irradiated foods over dehydrated ones, and would like milk, with some beer and wine.

On Skylab, crew members had problems with cans and packages floating around in the freezer and chiller, and tin cans rusting. They recommend packages be made square for more effective storage. They also found it difficult to transport large amounts of food from stowage lockers to the wardroom.

Food spill cleanup can be a problem if walls and ceilings are not designed for easy cleanup and nooks and crannies can be the source of undesirable odors. There is also a need for an adequate inventory system that is easy to use.

Hand and Foot Restraints - Easy to engage and disengage restraints to hold personnel in any required position and orientation should be provided in all work areas.

Lighting and Power Sources - Diffuse background lighting and flexible spot lighting should be available in all work areas. All lighting should have variable brightness controls. Power sources for spot lighting, power tools, and other equipment should be provided so as to minimize the need for power cords. Movement in dark areas should automatically activate lighting systems. Provision should be made to override the automatic lighting.

Storage - Easy storage and retrieval of supplies, equipment, and trash should be provided for all work areas. The storage should be arranged by general use of equipment (e.g., medical supplies not intermingled with electronics equipment). The storage drawers, cabinets, etc. should be clearly marked with easily understandable labels recognizable from any angle, (symbols and/or text to describe contents, not just a drawer number). It should be possible to examine the stored items while they are restrained from floating out. It should be easy to replace and secure items after removal from storage. Storage areas need adequate personnel and equipment restraints.

Explanatory Materials - Provisions should be made at all work areas to display instructions and graphics on paper and electronic displays. Provisions should also be made for writing paper and inputting data to electronic systems. It should be easy to position and orientate the paper and electronic media for required working positions.

Anthropometric Considerations - All IVA facilities should be designed to accommodate personnel from the five percentile female through the 95 percentile male, wearing either light clothers and barefoot or wearing shoes compatible with onboard foot restraint systems. As the station will be used for a long time, allow for a 30 year growth trend.

Critical displays and controls should be readily usable by all personnel within the normal ranges of deviation from standard proportions of body segments (e.g., arm length relative to body trunk length).

Bump Protection - Hatches and protruding equipment should have padding on points where passing personnel are likely to make contact.

2.5.2.1 Command and Control Stations

Command and control stations are multifunction workstations. The information load and/or cognitive workload for some functions are anticipated to be high.

Visual Displays - The visual displays should be multi-purpose and interchangeable. The displays should have high resolution and color capability.

These displays should be normally visually clean with neutral color and brightness, except to show required or requested information. (System status indicators are considered required information for visually clean displays.)

Two and three dimensional graphic representations and graphics with text should be used in displays instead of pure alphanumeric displays. Personnel should be able to easily reposition, reorientate, and reconfigure visual displays to optimize the workstation for various tasks, (e.g., panels may need to be reorientated depending upon one or two person operations.)

The use of colors in the displays should be consistent with the use of colors as specified by the Federal Aviation Administration, the United States Air Force, Navy, Army, and Marines for flight deck displays.

Red should be reserved for "warnings" of situations which require immediate attention and corrective action to insure successful completion of a critical task or mission.

Amber should be reserved for "caution" that a situation exists that could adversely affect a task or mission. Another, at this time unspecified color, should be reserved for "alerts" that is a malfunction or non-normal situation that presently does not threaten completion of a critical task or function.

The visual displays should be designed to automatically suppress non-critical information during emergencies or periods of high work load.

Auditory Displays - Auditory displays generally have high attention capturing characteristics, and can be good carriers of emotional or mood information. However, auditory displays provide for much lower rates of information inputs than visual displays. Also, it is difficult or impossible to scan auditory displays, and auditory inputs can disrupt task performance and visual information input.

Therefore auditory displays should be limited to high priority "warnings" and communications channels. Suppression of non-critical auditory displays should be at personnel discretion. Suppression should be automatic during critical events or periods of high workloads.

Command and data input should allow operators to choose a preferred input mode. For instance, input of a command from a displayed menu may be accomplished in the following ways: (a) depressing a point on a touch sensitive screen, (b) illuminating a spot on a screen with a light pen, (c) positioning a screen cursor with a trackball, mouse, joystick or cursor control keys, (d) keyboard input, (e) eye fixation using an eye movement monitor, and/or (f) voice inputs.

The operator should be allowed to choose from two or three of these options depending upon task requirements. The options should be standardized across tasks. It should be possible to interleave different types of inputs (e.g., keyboard, voice, keyboard).

Operators should be able to input commands either from a menu, or to bypass menus and to input sets of commands and options directly.

2.5.2.2 External Observation Stations

External observation tasks may require personnel to assume and maintain a wide range of positions and orientations. Observational equipment (cameras, sextants, etc.) may need to be maintained in fixed positions for extended periods of time.

Equipment Restraints - Equipment restraints should be provided for observation workstations which allow quick, easy precise positioning and holding of observational equipment.

Personnel Access and Restraints - Particular attention should be given to observational workstations to allow use of equipment for prolonged periods of time without assuming uncomfortable or painful body postures.

2.5.2.3 Human Research and Health Maintenance

The human research and medical workstations will support research on the effects of zero-g on personnel as well as support treatment of medical problems.

The human research and medical workstations may be combined with workstations for other purposes.

The requirements for sanitization for medical purposes restrict the options of combining medical stations with other workstations. The microscopes, etc., in medical stations lend themselves well to biological research. However, animal research stations should not be near medical workstations.

Examination of materials separated by electrophoresis could be done at medical workstations, if the materials were not medically hazardous (e.g., live virus).

2.5.2.4 General Work Stations

A number of work areas may be used for maintenance, repair, experimentation or other general types of work. Each of these areas should be designed for the particular functions to be performed there.

Work Tables or Benches - Provisions should be made for zero-g posture compatible tables, counter tops or benches on which to place and restrain equipment, tools, parts, instructions, manuals, etc.

Gases, Liquids and Solid Particles - Provisions should be made at all general workstations for collecting and containing benign and hazardous gases, liquids, and solid particles.

2.5.3 EVA Work Areas and Stations

The requirements for human/system interfaces for EVA work stations assumes an 8 psi, self contained, closed system, suit. The helmet should have electronically controlled eye visors to provide visual protection for abrupt changes from darkness to direct sunlight.

Personnel Containment - Positive personnel containment is an absolute requirement for all EVA work areas and passageways. This requirement can be handled by (a) containment structures or nets, (b) tethers, or (c) fail safe Manned Maneuvering Units (MMU).

Tethers restrict personnel movement, and require attention to prevent tangles. MMUs increase the mass to be managed, require manual (or voice) control during maneuvering, and can produce contamination by outgassing. Containment structures can allow for freedom of movement and the use of untethered tools and equipment. The containment structures or nets option is the preferred option whenever feasible.

Visual Perception - The properties of the human visual system merit special attention in designing EVA work areas. Certain arrangements of equipment could allow for extremely high contrast visual fields (e.g., sunlit reflective gridworks or trusses viewed against dark sky). High contrast visual fields tend to fatigue portions of the visual system. This fatigue can produce visual after-effects, irritability and in extreme cases, possibly even damage to the visual system.

The EVA visual environment can be made more benign by providing diffuse light sources and visually textured backgrounds.

The visual perceptions and judgments of size, distance, and relative motion is based upon a comparative process. Comparisons are continuously made between the object being evaluated (a figure) and another object or objects (the background).

Visual perception is more accurate when the background contains features, and is relatively close to the figure being evaluated. Space is a relatively poor background for visual perception of nearby objects. Providing backgrounds with features for EVA work areas could greatly improve the visual perception of size, distance and motion of objects. This would improve the safety and efficiency of EVA personnel. Note: Backgrounds that are rich in features tend to camouflage or conceal stationary objects.

EVA Suit Protection - EVA personnel are dependent upon the pressurization of their space suits. Any holes, cuts or tears in a suit places the wearer's life in jeopardy. All EVA work areas, passageways, facilities, equipment and tools must be designed and constructed so as to minimize the probability of damaging the pressurization capabilities of space suits.

Restraints - Provisions should be made for convenient foot and hand restraints in all EVA work areas. The hand restraints should allow for easy change in personnel orientation, and motion. Hand restraints should be provided in all personnel traffic areas as well as where personnel must stop or position themselves.

Foot restraints should be placed wherever personnel must maintain a position for more than just a few moments, or wherever torques must be applied. The foot restraints should allow personnel to assume the correct position and orientation for equipment access. Foot restraints should allow personnel to either rotate around a point or establish and maintain an orientation. The foot restraints should have easy, quick, fail safe, positioning and locking and unlocking capabilities.

Portable hand and foot restraints and mounting facilities should be provided to facilitate proper restraint positioning and orientation.

2.5.3.1 EVA Work Stations

All EVA workstations displays and controls should be designed to accommodate personnel from the five percentile female through the 95 percentile male, wearing a closed system 8 psi suit. In addition, critical displays and controls should be readily usable by all personnel within the normal ranges of deviation from standard proportions of body segments (e.g., arm length relative to body trunk length).

All hand operated controls are to be designed to be used by personnel wearing 8 psi gloves. Tactile cues should be provided to allow nonvisual discrimination between adjacent controls. When possible, controls should provide tactile feedback of activation.

Displays should be clearly visible in all anticipated lighting conditions. Background lighting should be diffused and not cast dark shadows from personnel on work surfaces. Provisions should be provided to easily modify the direction and brightness of background lighting and the brightness and contrast of displays. Display and background lighting should automatically adjust to changing lighting situations (e.g., sunlit or darkside earth). Movement in dark areas should automatically activate lighting systems. Provision should be made to override the automatic lighting

2.5.3.2 EVA Passageways and Access Areas

Structures and equipment should be located so as to minimize the probability of contact by passing personnel. Structures and equipment should be designed so as to not injure passing personnel or damage their space suits.

Where tethers may be used, structures and equipment shall be designed to minimize tether entanglement and to facilitate tether untangling.

Where MMUs use is anticipated, provisions should be made for easy access to all critical parts by MMU equipped personnel.

If RMS secured personnel are to work on equipment, all critical parts should be positioned and orientated to allow easy access by RMS secured personnel.

Workstations should not be located in airlocks or other passageways.

Airlock - The airlock should be dedicated to EVA egress and ingress only. It should be outside the traffic flow, yet easily accessible to suited crew members. Restraints should be provided to protect cameras and other equipment during repressurization and during EVA preparations.

2.5.4 General Maintenance Considerations

Neither Skylab nor the Shuttle were designed for on-orbit maintenance. Major repairs and modifications had to be accomplished on Skylab several times in order to save the mission. Much of the critical repair work had to be conducted EVA. Early Shuttle flights required on-orbit repair in order to perform mission tasks. Skylab and Shuttle repair has been severely impacted by the failure to design for on-orbit maintenance and repair. The primary maintenance areas for the space station are abilty to test, access, control of power, fluid and gases, maintenance tools and equipment, maintenance information, training and scheduling.

Ability to Test - All Space Station facilities and equipment should be designed for easy, reliable, on-orbit monitoring and testing. Operating systems should have built-in self-test and diagnosis systems. Critical life-limited components/subsystems should have continuous self-tests. Any negative results of the self tests should be immediately displayed on-orbit and on-ground. The systems should be easy to recalibrate and should provide information in easy to understand displays and formats.

Provisions should be made for using standard test equipment on equipment or functions that do not have self-test.

All tests points should be easily locatable and accessible. Test results must be "truthful" (e.g., a power on light should mean that the circuit has full electric power, not just that the switch is in the on position).

Access - Equipment which is not accessible is not maintainable. Any equipment which may need to be serviced, repaired, or replaced must be easy to inspect visually, test, disassembled, reassemble and remove.

Adequate access may be provided by (a) constructing and installing equipment to provide direct access to components, or (b) by allowing for easy removal and replacement of anything that restricts access.

All fasteners should be quick disconnect and reconnect. Fastener parts should be captive (will not float when removed). Fasteners should not require special tools or large torques.

Wire harnesses and connectors should not hinder access.

Provisions should be made for proper hand, foot and tool restraints while personnel inspecting, testing, servicing, repairing or replacing equipment.

Procedures for access and closure should be on labels attached to equipment.

Power, Fluids and Gases - The electrical power systems, hydraulic and other fluid systems, and gaseous systems must all be designed for safe maintainability.

Power systems should be easily reconfigurable. Line replaceable items should be at low levels. Any one remote power controller should only power a few units.

Power switches and circuit breakers should be readily accessible, but protected from inadvertent activation. Indicator lights should give positive information of power on or off.
The location of remote switches, circuit breakers or power units for a piece of equipment should be indicated on a label on the equipment. Conversely, labels on switches, circuit breakers and power units should tell what circuits and equipment they control.

Tools and Equipment - Whenever possible the tools and equipment used for maintenance and repair should be standard off-the-shelf tools. The tools should be stored in the area where they will be used. If a particular type of tool is intended to be used in two or more locations in the space station, a copy of the tool should be stored in each location in which it will be used. The tools in each area should include safety equipment (e.g., safety goggles, gloves).

Power tools and test equipment should be battery powered whenever possible. Electric outlets should be provided at close intervals for electric tools and equipment without batteries.

Maintenance Information - Frequently used maintenance information for a piece of equipment should be attached to the equipment, or stored nearby. Complete information should be readily available (e.g., video terminals, duplicate copies of manuals).

Maintenance information should include as many pictures and illustrations as possible. Motion pictures, or quick sequence pictures should be provided for complicated operations.

Microfiche - Those with experience recommend against use of microfiche systems as a practical device because it is not easily accessed at work sites.

Tech writers and film makers should write or edit the maintenance information. The effectiveness of the information access system, and individual sets of instructions, should be ground tested prior to flight. The tests should be conducted with personnel who were not familiar with the equipment or the maintenance information.

Training and Scheduling - Mission timelines should allow for both planned and unplanned maintenance and repair. The preflight maintenance training is dependent upon the mission schedule. Some flight periods may be scheduled for concentrated maintenance and will require extensive preflight maintenance training.

Maintenance training should cover flight critical items, mission critical items, and anticipated frequent procedures.

3.0 DATA MANAGEMENT SUBSYSTEM

3.1 INTRODUCTION

The space station data management subsystem is a data processing system that consists of a collection of processing elements, mass memory elements and communication links. It provides for central processing and data base management and for subsystem control and status monitoring. Definition of the system requires selection of the processing architecture, the data transmission scheme, the processors and mass memory devices. The full report on the topics discussed in the following subsection are found in the Volume 7-4 Data Book.

3.2 ARCHITECTURE

In establishing the system architecture, the following issues must be addressed:

- Topology
- Communication
    - Characteristics
    - Protocol
    - Media
- Processors
- Mass Memory
- Controls and Displays

Selection of the topology first requires definition of the processing and communication requirements. The first step is to identify the number of processing nodes and the location of each. Typically these will correspond to the various subsystems, plus a control processor for human interface to the system. The next task is to identify the communication requirements. These may be compiled using a matrix as shown in Figure 2.3-1. Entries indicate the amount of data required per unit time and the direction of data flow. Entries may also contain additional information such as burst vs. average, video data, etc. The next requirement is to define how the data rates change as a function of time, mission, mission phase, application, etc.

The interconnect topology can take various forms as shown in Figure 2.3-2. The characteristics of each of the schemes are optimized around different attributes at shown in Figure 2.3-3. As a separate input to the topology development, the fault tolerance requirements must be defined for various processing nodes and for the system. Because of the complexity of the

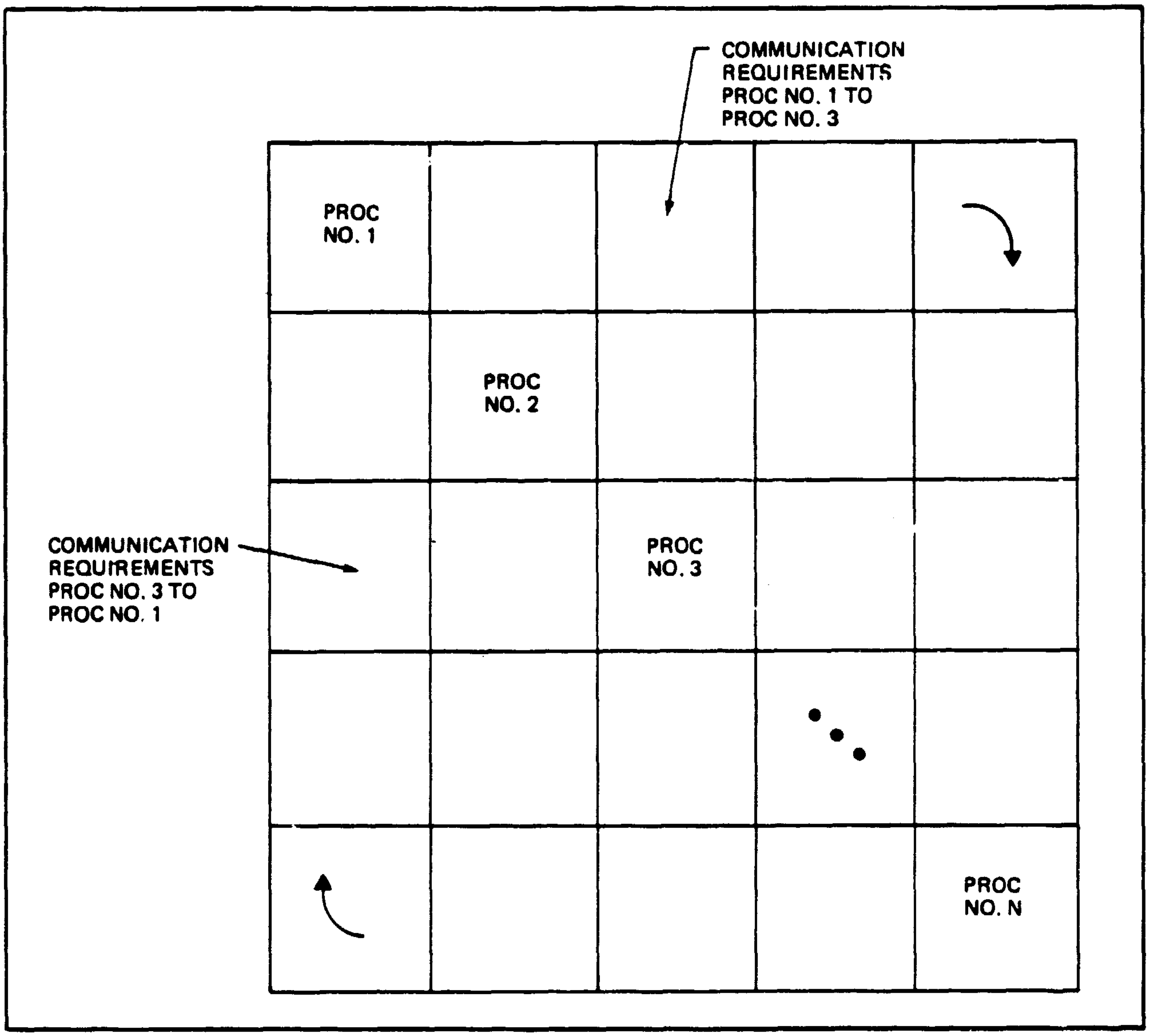

Figure 2.3-1. Interprocessor Communication Matrix

communication requirement and the severity of the fault tolerance requirement, it is necessary to model the communication of the most promising topologies, making assumptions about the failure rate of processing nodes, communication protocol and mission scenarios. This then allows analysis of the communication statistics and fault tolerance for each candidate over significant operating periods. The analyses of the topology alternatives may need to be iterated as various communication characteristics/protocols and processors are defined in response to topology selections.

An additional criterion that must be considered in the topology selection is identification and accommodation of physical interfaces in the space station. It is desirable to minimize the number of communication links that cross each physical disconnect interface. This reduces connection complexity and susceptability to faults.

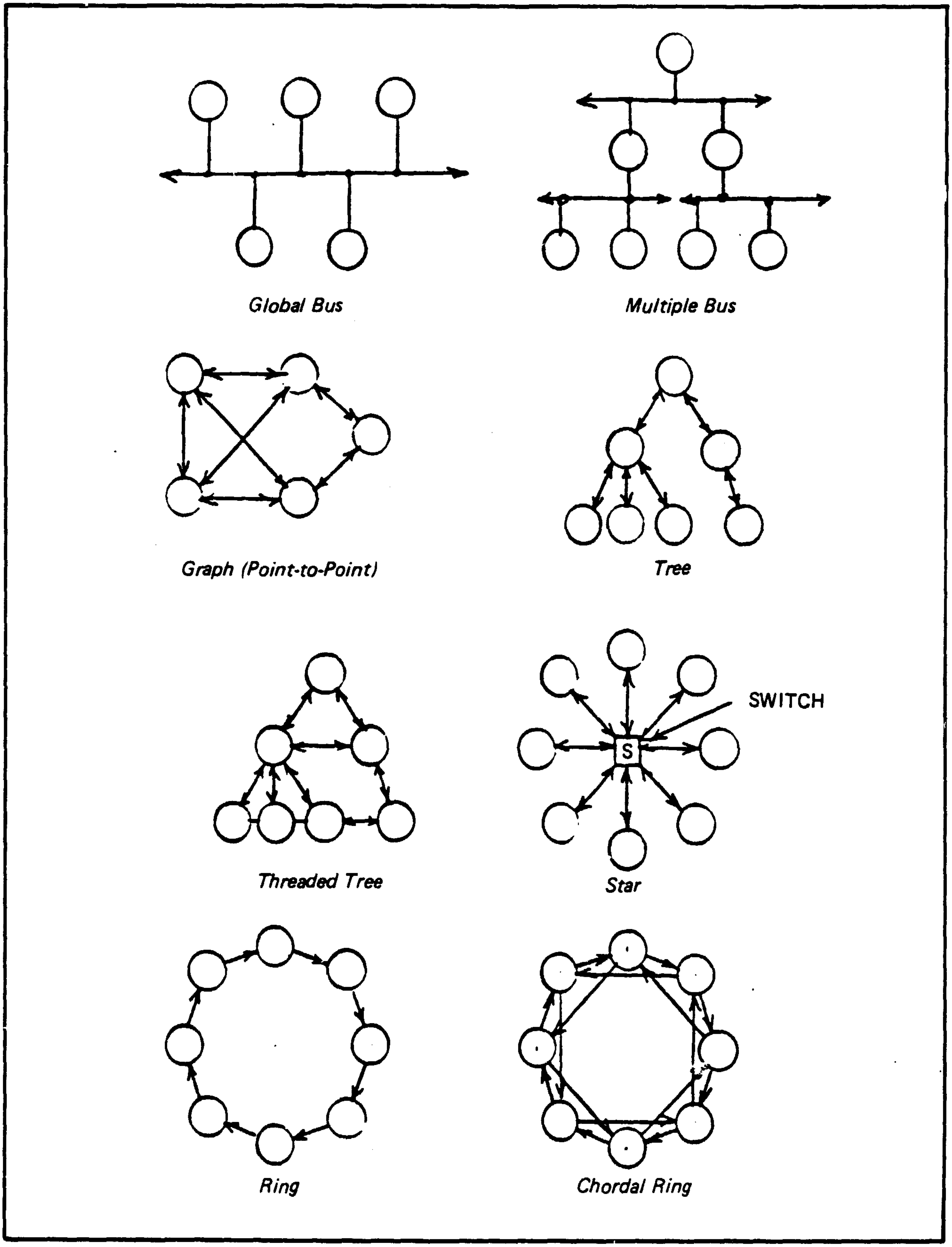

Figure 2.3-2. Computer Architecture Topologies

DISPLAY	LUMINOUS EFFICIENCY (LUMENS/WATT)	RESOLUTION RANGE (LINES/CM (LINES/INCH)	COLOR CAPABILITY	GRAY SCALE LEVELS	DOT MATRIX ARRAY SIZE (H X W)	DISPLAY AREA H X W	MAXIMUM VOLTAGE REQUIRED	LIFETIME (HOURS)
CRT MONOCHROME	10	26 - 43 (65 - 110)	MONOCHROME	256	2000 X 2000	75cm DIAGONAL	12 - 18keV	2,000 – 10,000
(BEAM PENETRATION)	4	26 - 43 (65 - 100)	RED – GREEN	256	2000 X 2000	48cm DIAGONAL	10 - 20keV	2,000 – 10,000
(SHADOW MASK)	3	32 (80)	RED – GREEN – BLUE	256	1C24 X 1280	75cm DIAGONAL	10 - 25keV	>15,000
LED	0.1	13 - 51 (32 - 128)	RED – GREEN	8	256 X 320	10 X 12.5cm	10V	>11,500
LCD	PASSIVE	12 - 20 (30 - 50)	BLACK, BLUE, GREEN,YELLOW, RED (SINGLE)	8	280 X 360	15 X 18cm	3 - 20V	>50,000
EL	1 - 8	28 (70)	YELLOW – ORANGE (SINGLE)	16	240 X 320	9 X 12cm	100 - 200V	>50,000
PLASMA	.3 - 3	12 - 24 (30 - 60)	ORANGE, GREEN (SINGLE)	2	1024 X 1029	1m X 1m	100 - 200V	>20,000
VF	4 - 6	20 (50)	BLUE – GREEN (SINGLE)	16	128 X 128	7.7 X 7.7cm	30 - 80V	>30,000

Figure 2.3-3. Display Parameter Comparison

For the communication links, various candidate approaches should be identified. For each of these, the various characteristics need to be defined: speed, electrical characteristics, noise immunity, data limitations, overhead, limitations on transmission media, limitations on protocol, etc. These then need to be compared to the requirements defined for the topology to determine suitability for each of the various alternatives. Standard communication approaches are preferred, especially when the system is to use elements already developed or in development, or is expected to use elements which are interchangeable with another system.

The various protocols need to be traded with respect to the candidate topologies to determine system communication capability and susceptibility to faults. As part of the evaluation of the protocols and the topologies it is necessary to evaluate various system control procedures. These control the flow of data as a function of the processing requirements and the switching of communication links in response to failures. The system control procedures will reflect the simplicity, modularity, expandability and fault tolerance of the topology and the data transmission characteristics and protocol.

Selection of the transmission media is somewhat a function of the communication scheme selected. Standard communication schemes most often specify either directly or indirectly the transmission media. There is an option to modify the standard to the extent necessary to allow another medium. Selection of the medium involves analysis of the options with respect to weight, transmission length, durability, security, etc. The results of this analysis may affect the topology or communication scheme selection.

Selection of the processors involves analysis of the processing requirements at each processing node (subsystem). This includes processing load (operations per second for a specific processing task, i.e., instruction mix) memory requirements, interface to the supervisory system, and subsystem unique interfaces for data collection, control and status monitoring. Additional criteria to be considered include fault tolerance requirements, standardization among various subsystems, use of standard processor instruction sets, availability of programming languages, modularity of processor components, fault tolerance, and test and maintenance capability.

Selection of the system mass memory is somewhat independent of the above considerations except to the extent that location of the devices affects data communications and hence the topology and communication scheme. To define the mass memory requirements involves listing the various blocks of data, their size, where the data is generated and/or used, whether the required access is read only, write only or read/write, and any memory protection requirements. With this information, various combinations of device type and locations of devices can be traded off in conjunction with the topology selection and the communication scheme.

For the Space Station, the display selection methodology should consider the use of flat panel displays where the system requirements permit. For those areas currently requiring CRT's, the driving hardware should be designed to permit the installation of flat panel displays as their technology advances. Displays should be capable of operating in a multifunction mode to minimize hardware required for each system. Figure 2.3-4 shows some of the available display options and characteristics for both flat panel and CRT displays.

CHARACTERISTICS

Candidates	Fault Tolerance	Bandwidth	Simplicity	Expandability
GLOBAL BUS	3	1	5	5
MULTIPLE BUS	4	3	4	4
GRAPH (POINT TO POINT)	5	5	1	1
TREE	2	3	3	3
THREADED TREE	4	4	2	2
STAR	1	1	5	4
RING	1	1	5	5
CHORDAL RING	5	3	4	4

RELATIVE COMPARISON 5-BEST

Figure 2.3-4. Comparison of Topologies

Crew interaction with subsystems should be minimal in keeping with the concept of automatic operation. The crew should be presented with only the information they request or need to know. This information should be concerned with the following areas:

1. System status indication
2. Caution and warning indications
3. Data necessary for performance of crew repair and/or resupply
4. Selection of alternate automatic operating modes.

The question of degree of automation with respect to checkout, maintenance fault isolation and fault tolerant corrective action will depend on the amount of supervisory command control

which the crew is willing to delegate to the automatic system. The crew should be able to call up any of the data upon which the system bases the initiative of a corrective or preventive action. Whether the crew would want veto power over some or all of these actions would depend on the history of operating experience with the subsystem. As more experience is obtained and the operation of the automatic features is verified, a greater portion of the off-nominal operation could be relinquished by the crew. The goal of system design and operations should be to provide automatic fault correction or bypass, with concurrent notification of current status to the crew for the most common faults. The correction of less common faults might be left to the crew depending on the costs in time and funding necessary to automate these corrections.

As the technology matures the use of expert systems should be considered. In general, expert systems are well suited as replacements for specialists whose skills are in short supply. For example, on a mature space station, it is unlikely a small crew would be master of all the skills necessary to respond to all possible contingencies. Expert system diagnostic and repair advisors are desirable for subsystems whose failure is immediately life-threatening. Applications for which expert systems could be considered include:

a. equipment fault diagnosis
b. medical diagnosis
c. signal interpretation
d. robotics
e. planning
f. system control
g. system monitoring

3.3 IN-FLIGHT CHECKOUT AND MONITORING

The requirement for in-flight checkout and spacecraft system monitoring has gradually increased with each space program. The Shuttle, with its system management and failure detection and isolation capabilities is the most sophisticated to date. The Space Station Program will force a new approach to in-flight checkout and monitoring. This will be the first space program in which the mission duration will exceed the mean-time-between-failure (MTBF) of every electronic device on-board. On all previous programs, the missions were short compared to the MTBF of the components. Between each mission and ground checkout operation assessed the readiness of every component, and caused replacement if necessary. Therefore, the reliability clock started anew at lift-off of each mission.

The Space Station Data Management System (DMS), because of this certain MTBF exceedance, must be designed not only to react to observed failures, but to detect potentially latent failures of components, especially those which are installed to sense and flag dangerous situations. The measures required to detect such failures are not immediately obvious for sensors such as those which may be embedded in a cryogenic tank or an inaccessible part of the structure. If direct stimuli cannot be provided for this class of sensors on the Space Station, other measures such as redundancy, periodic replacement, or correlative data may be required.

Another aspect of the Space Station mission will force new and innovative techniques. The normal resupply and/or expansion operation will result in the delivery and attachment of a module which has been essentially inert through ascent and rendezvous. Such modules will require activation and checkout before use. These operations could be carried out with on board resources only but would be enhanced by the appropriate level of ground involvement.

3.4 SPACE-GROUND INTERACTION

To be viable economically, the Space Station Program must develop a space/ground responsibility allocation which allows a much smaller, less expensive ground operational support environment than utilized on previous programs. The mission environment with its more-or-less constant orbital characteristics, should be relatively stable and amenable to on-board flight planning. Day-to-day operations should be largely concerned with station system monitoring, housekeeping, and experiment servicing. Occasional periods of intense ground interaction may occur when modules are added or replaced or when major configuration changes occur. The norm however, should be on board control with ground support as required.

The modern network approach described below for the ground-based software development complex should be extended to include the Space Station DMS as a very smart remote terminal. Assuming appropriate protection and/or isolation of critical functions, this would provide the optimum interface between experimenters and their experiments, between ground subsystem personnel and their subsystems, and between ground and on board mission and flight planners.

To realize this, the ground complex, operational as well as experiment oriented, must utilize common or compatible software standards. Further, the software standards chosen must be sufficiently flexible to accommodate the unknown but certainly wide-ranging nature of 20 years of operations.

3.5 GROUND LABORATORY COMPLEX

Several Space Station program characteristics tend to mitigate the stringent requirements for ground laboratory complexes experienced on previous programs. The avionics state-of-the-art is well within that required for the Data Management System (DMS). The DMS design should have few, if any, "high risk" or even "uncertain" features, but rather should utilize proven technology. The mission environment should be much more benign, with fewer critical aspects than the Shuttle (no ascent or entry phase). Orbital assembly, checkout and final systems validation will be conducted with the Shuttle attached or in the near vicinity, and therefore will entail minimal crew risk. Few if any mission operations are so time critical, either in sequencing precision or reaction time, as to prevent manual monitoring and intervention if required.

Flight control system requirements will probably be limited to vernier control of a gravity gradient stabilized structure and to orbital make-up translations. The most difficult task will be to accommodate the wide variation in structural characteristics which will occur as modules are added and removed, and as the station expands. The accommodation could take the form of an adaptive system or one which is updated stepwise, manually or automatically, as the configuration changes. In either case, the control authority will be relatively low and the response times slow, and therefore the system will be manually monitorable and overrideable. While all these considerations tend to reduce to some degree the need for "absolute" proof testing before lift-off, the most overriding factor is cost. The development and operation of a laboratory such as The Shuttle Avionics Integration Laboratory is extremely expensive. The cost of building and maintaining such a facility for the twenty-year Space Station program would be tough. Therefore an alternative approach should be found.

A final consideration, and one which may provide a solution to part of the problem is the Space Station itself. In contrast to previous programs which were characterized by relatively brief missions, each generally containing some new and untried aspect, the Space Station, once placed in orbit will operate continuously for the life of the program. After an operational state is achieved, and especially if the environment proves benign as postulated above, the Station may serve as its own laboratory to a large degree. In any case, its attributes should be considered in any laboratory planning activity.

Ground laboratory requirements can be considered from two aspects: the test and validation operation to be performed prior to initial orbital installation; and the operations in support of

growth, change and update after the initial configuration becomes operational. The objective is to find an approach which supports the initial phase but which does not result in an investment in ground facilities beyond that required for the operational phase. In this scenario, a software development laboratory (SDL) is assumed to exist, containing actual computer hardware and simulations or emulations of all peripheral devices, and capable of closed-loop simulation of all mission operations.

In the Shuttle, SDL testing was deemed inadequate for final system validation because of the restricted amount of flight hardware, the difficulty in certifying models, and an inability to incorporate noise, delays and other effects of actual vehicle wiring. For the Space Station, however, after initial operational capability, each model and simulated aspect of the SDL can be directly correlated with actual flight performance and modified to match if required. If this correlation is conducted properly, the SDL should be able to perform most, if not all, the required ground verification and validation tasks for software updates or modifications in the operational phase.

Prior to the initial operational capability, however, the SDL must be augmented by higher fidelity hardware and hardware/software integration tests. In previous programs, this integration required an extensive closed-loop simulation capability to adequately exercise and stress the flight hardware in all mission phases. The set up included elaborate schemes for extracting outputs from and inserting inputs into the flight article in a way which did not disturb system integrity. The complexity of this operation and the length of the validation program were such that a dedicated shipset of avionics hardware an an elaborate laboratory complex was required. Much of the complexity however, and most of the time were attributable to the ascent and entry phases. If on-orbit operations only had been involved, the need for such an elaborate validation program and laboratory complex would have been significantly reduced. While the prime requirement for the DMS validation program should be, as always, to ascertain that the system operates correctly with the flight hardware connected in as close to the flight configuration as possible, a much less costly approach might be possible.

One scenario would use actual space modules connected as in flight to perform the required preflight verification. The modules could be developmental or boilerplate if near enough in fidelity to the flight articles. If not, the actual flight modules could be utilized and the validation scheduled as part of the preflight build and checkout flow. The latter option, of course, would entail the risk of uncovering a fault late in the program and a potential schedule slip. This one time program risk should be traded off against the cost of higher fidelity developmental modules or even against the cost of a SAIL type facility.

The complexity of support equipment required to perform validation using spacecraft modules operating in a static ground environment will depend on the software design and the facility with which peripheral subsystem equipment can be made to simulate in-space activities. The software, subsystems, and the spacecraft modules should be designed to accommodate and simplify the validation task.

In summary, the unique characteristics of the Space Station Program and the mission environment offer the possibility for minimal (by Shuttle standards) investment in large ground laboratory complexes.

3.6 SOFTWARE DEVELOPMENT APPROACH

The Space Station program will begin with a significant software legacy from the Shuttle program. The Software Development Laboratory (SDL)/Software Production Facility (SPF), developed at Johnson Space Center for Shuttle contains an extensive suite of hardware, software development tools, and personnel expertise which can serve as a springboard from which to launch the Space Station program. In addition, the in-place team is fresh from the successful development, verification and flight of the shuttle avionics system. This system contains a software package which, in addition to the application modules, includes a sophisticated asynchronous operating system, redundant computer sychronization schemes, redundancy management techniques, memory management features, and crew interface and display processes. Much of this capability is directly applicable to the Space Station program.

There are however, a number of aspects of the Space Station program which have not been encountered previously. The increasing utilization of software for control of systems which relied on mechanical, analog, or manual measures on past programs will pose a new management and control problem. The Shuttle program relied on the use of software requirements documents produced and integrated by the prime spacecraft contractor, as software specifications for the software contractor, who then coded (or integrated) all flight software. The Space Station will probably have a number of associate contractors and subcontractors—many with embedded micros or dedicated standalone processors. In contrast to the Shuttle era, most of these contractors will have acquired credible software expertise, therefore producing all code with one source as in the Shuttle mode may not be appropriate.

Several other aspects of the Space Station program may force differences in the approach to software development. The 20 year program length with certain, but undefined growth

requirements will require development of new techniques for software program evolution, change, and probably some degree of final on-board validation. A much greater degree of space/ground interaction can be expected in the experiment processes area. Finally, the amount of software to be developed will be so great as to require significant reduction in the cost per software unit if the program is to succeed.

Fortunately, a number of advances in the software development process and in other related processes have occurred in the past decade which hold the promise of increasing production efficiency. Program Design Languages (PDL) are emerging as a useful first step in program design. While intended to support the design process, PDL's can also simplify the transition from requirements to code. Extensive networking is now economically feasible tying computers and users, widely separated geographically, together in an integrated development environment.

As stated above, the software will be utilized by virtually all subsystems and functional processes in the Space Station. The code may reside in a range of processors, from embedded micros to dedicated, isolated stand alone computers to general purpose supervisory systems. Functions may have interactive code located in all three classes. The embedded microprocessors, and possibly some of the dedicated machines will probably make use of Programmable Read Only Memory (PROM) for protection of critical functions. The subsystem design process will in many cases, involve much closer hardware/software iteration than was the general case in the Shuttle.

In such an atmosphere, the Shuttle concept of relying on a single software contractor to generate all code in response to written NASA baselined, requirements, would be extremely unwieldy and inefficient. On the other hand, the requirement for central integration and the desire for NASA control of the system would mitigate against a total decentralized concept in which software was developed independently by each subsystem area and delivered with the system. A hybrid concept, which allows for the necessary iterative subsystem design process, yet provides for the required upward and cross-subsystem integration as well as NASA visibility and control should be the goal.

One scenario which appears to satisfy most requirements would be a concept in which a central software development, integration, and verification facility would be maintained by NASA (and presumably its software contractor). The facility would house the complete suite of tools included in the selected standard software development environment; a complete data base containing all information pertinent to the software design, integration and verification process (requirements, PDL, source code, wire and instrumentation lists, spacecraft data, display

formats, etc.); and the simulations, emulations and other capabilities required for integration and verification. This central facility would be accessible, via a dedicated network, to all contractors (and appropriate government organizations). The use and interaction with the facility by the various contractors would depend on the nature of the software involved. If the subsystem application required no software interaction external to the subsystem, it might be possible for the contractor to develop the software on a microprocessor development system (MDS) and to use the network only for transmittal of requirements, source code, and other data required in the configuration control process. The embedded microprocessor and the associated MDS would presumably either be government furnished or bought to a NASA-dictated standard.

If the system application warranted a dedicated stand alone machine (or machines), possibly with micros embedded in peripheral equipment, i.e., a Guidance and Control (G&C) system, the use of the network would be much more extensive. The G&C contractor would utilize the central data base as the only approved source of pertinent information (structural, aero, venting, instrumentation, display, etc.) and would be responsible for maintaining performance records as appropriate. The G&C software would be developed on "SMART" remote terminals but use the central facility compilation, debug, and other development tools. Integration of the G&C software with other subsystems and with supervisory systems, and verification of the total package, would be performed in the central facility supported by the G&C and other contractors.

If a subsystem application did not warrant either an embedded micro or a stand alone machine, but did require software services residing in the supervisory system, the development process would be similar to the Shuttle, with the software contractor furnishing code based on requirements from the system contractor. Here again, the network would be used for transmittal of requirements and data, and the receipt of resulting code.

The scenario outlined above could have many variations but the main theme should be pursued vigorously. That is - to utilize modern techniques for networking, data base management, requirements development (and translation to software design), code production, verification, and configuration control - to reduce the Space Station software to an affordable level.

3.7 HARDWARE STANDARDS

The data processing hardware available today, from many sources, would appear more than capable of accommodating the Space Station requirements. All three military services are developing standards for applications comparable to that of the Space Station in complexity.

The Air Force has invoked a standard 16-bit instruction set architecture (ISA), MIL STDD 1750A. Measures are under study to insure that the ISA and associated software can be applied to a spectrum of machine capabilities from mini-class to embedded micros. The Army is exploiting the same concepts in its 32-bit ISA, MIL-STD-1862, (NEBULA) Military Computer Family (MCF) program. The Nebula program schedule follows that of the Air Force but, as a result, is the first military standard ISA to be developed with the new DoD standard language, Ada, in mind.

The Navy is also standardizing on a new set of shipboard and weapons system computers. These include the AN/UYK-43 standard large shipboard computer and the AN/UYK-44 Militarized Reconfigurable Processor (MRP) series currently under development. The MRP can be configured either as a stand alone computer or as a card level embedded application, both with a wide range of capabilities. All three of the above military developments are addressing the system interconnect problem and are attempting to provide a building block, easy-to-configure system capability.

In addition to the military, a wide range of capabilities are available commercially. Several companies market a series of machines, from mini to micro, software and interconnect compatible, which appear adequate for the Space Station task. Some have off-shoots manufactured to MIL-SPEC standards. Most have an extensive library of software and software development tools and are committed to maintain upward system compatibility for new developments. This committment is particularly attractive for a 20-year program.

A potentially appealing alternative to one of the military standards, especially if program schedules require early provision of DMS hardware, might be an initial competition to select a commercial line which qualifies from a performance, capability, and development environment aspect. Then, while the various subsystems use the selected off-the-shelf hardware in their development, to contract for repackaging the hardware, maintaining one-to-one software compatibility, to space environmental qualifications. This alternative is particularly attractive if a Space Station environmental analysis proves that near-commercial quality is adequate.

3.8 SOFTWARE STANDARDS

The HAL/S language developed for the Shuttle program, and the accompanying development and support environment and the personnel expertise which has accumulated in NASA and associated contractors represents a significant in-place resource which would probably be adequate for the Space Station. The major DoD thrust toward the new language Ada and its

integrated support environment is so significant and all-encompassing however, that it makes the retention of HAL/S questionable. Ada incorporates the latest state-of-the-art features and capabilities which, if realized, could reduce the Space Station software life-cycle cost. If the new system is accepted and promoted to the degree which now appears likely, it will be difficult for NASA to retain and maintain HAL/S capability over the 20-year life of the program. The new DoD Software Initiative program, which uses Ada as its cornerstone, should accrue benefits over the next several years which would have direct applicability if the Space Station adopts the Ada system.

The only significant issue pertaining to the Ada/HAL/S selection other than the cost to NASA of the initial transition, is the question of Ada maturity. If the Space Station schedule precedes the use of Ada by the DoD on a significant program, it may be necessary to begin the program using the existing HAL/S environment and to plan a transition to Ada at the appropriate time. Both Ada and HAL/S should be evaluated to explore methods for making such a transition as simple as possible.

3.9 VERIFICATION AND VALIDATION

The distributed Data Management System concept envisioned for the Space Station affords an opportunity to examine new approaches to the verification and validation of the on-board software. The philosophy on previous manned space programs such as Apollo and Space Shuttle was to prove to the maximum extent possible before flight that the software, and system, would perform the prescribed functions properly, and above all, would not jeopardize the safety of the crew. The approach used was to exhaustively test the software and system in laboratories that emulated the space system and the dynamic environment with as much fidelity as could be devised over a spectrum of conditions which covered all portions of the flight envelope and every conceivable uncertainty, variation of parameter, and mission contingency. This approach to verification, while obviously successful, is extremely expensive and time consuming and may not be feasible in the Space Station Program. While it is not possible to deviate from the philosophy that mission success and crew safety must be assured, the unique character of the Space Station, the mission and the baseline system may allow or even force the use of new approaches.

In a distributed system, it is possible to segregate and isolate critical functions and thereby prevent or reduce the possibility of interaction between modules. A critical function such as flight control may be mechanized in a dedicated processor, or group of processors if redundancy is required. Flight control sensors and effectors could be assessed and commanded via a dedicated bus system. The flight control software could be contained in read only memory, thus

preventing the possibility of inadvertent write-overs from the mass memory system. Verification of the flight control software in such a system would be a much simpler task than in a centralized system. With proper isolation the verification standards applied to non-critical functions could conceivably be relaxed because of the reduced risk of interaction with critical functions.

To realize significant benefits, verification and validation considerations must be given appropriate weight in the Data Management System design trade process. The allocation of functions among processor and the selection of system architecture and data bus network concept are of particular importance. If may be that the classical disciplinary distribution of functions, i.e., Guidance and Navigation, Flight Control, Communication, Electrical Power, Displays and Controls, etc., will provide to be inappropriate from the verification aspect and therefore a different allocation algorithm may be required. The desire for functional isolation may drive the system architecture in the hierarchical direction. Although verification/validation attributes have never driven the design process on previous programs, it appears that the potential for recurring cost savings in the verification process is great enough for serious consideration in the Space Station.

The Space Station configuration and the nature of the operations to be performed also present an opportunity to explore novel, cheaper verification/validation techniques. In a program such as the Space Shuttle, the vehicle configuration and mission operations generated requirements for precise sequencing and extremely fast reaction times. For instance, during ascent and entry phases, an inadvertent flight control actuator hardover could be tolerated for no more than 100 milliseconds or the vehicle would suffer catastrophic structural damage. Therefore the ability of the crew to monitor or override the system was limited, an automatic reaction was required, and the preflight verification/validation process alone had to be relied upon to provide assurance of mission and crew safety.

The Space Station mission operations, in contrast, are generally characterized by relatively slow sequencing and reaction time requirements. Performance should be easily monitorable by the crew and override or other intervention should be possible. Under these conditions, where no catastrophic effects are possible, it may be appropriate to reduce verification rigor on the ground at the risk of finding a bug on board. It is unlikely that such a reduction in rigor could be considered for the initial Space Station configuration; however, it might be possible for updates, modifications or add-ons after the program matures.

4.0 COMMUNICATIONS AND TRACKING SUBSYSTEM

4.1 INTRODUCTION

Our subcontractor, RCA - Astroelectronics, was asked to critique the Space Operations Center (SOC) communications and tracking subsystem concept. This task was undertaken for the following reasons:

1. The SOC communications and tracking subsystem description represents the results of the most detailed communications subsystem analysis conducted for a space station concept since 1972,
2. This subsystem concept will, therefore, be used as a reference in the current space station design, but
3. Communications requirements were updated since the most recent definition update.
4. The concept has not received any detailed critique outside of Boeing.

This subsection gives an overview of the approach and the results. The reader is referred to Volume 7-4 - Data Book for the complete report on this topic.

4.2 APPROACH

The SOC communications and tracking subsystem description was given in Boeing Document D180-26495-3, Rev. A., SOC System Analysis, Final Report, Volume 3, System Definition Document, January 1982 (Reference 1). Figure 2.4-1 shows the communication linkages. Figure 2.4-2 shows the SOC antenna locations. (Refer to Reference 1 pp. 263FF, for complete description of SOC communications and tracking subsystem).

This subsystem description was compared to the requirements put forth in Boeing Document D180-26495-2, Rev. A, SOC System Analysis, Final Report, Volume 2, Requirements for a Space Operations Center, January 1982. (Reference 2) and the Space Station Program Description Document, System Requirements and Characteristics, Book 3, First Edition, November 1982, (Reference 3). Compliance or non-compliance to these requirements were evaluated and described.

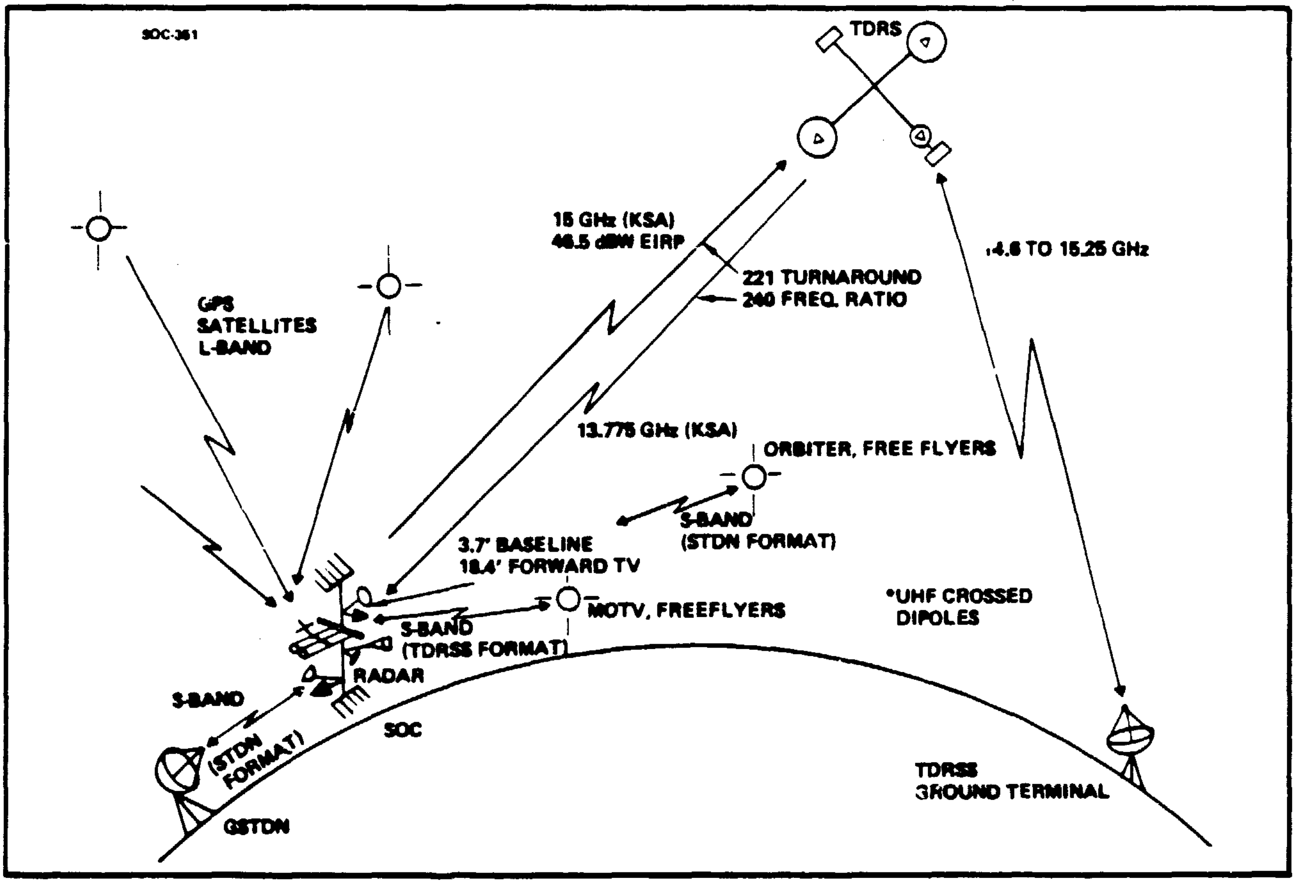

Figure 2.4-1. SOC Communications Linkages

4.3 RESULTS

The SOC communications subsystem design does not meet the specified requirements in the areas discussed below:

The operating range (distance) requirements for EVA communications, SOC-orbiter, SOC-OTV and SOC-free flyer communications are not met.

Television coverage from EVA users, OTV and free-flyers is not provided, as required.

Two duplex voice channels between SOC and orbiter are required (one is provided), a command link for orbiter to SOC is required (not provided). Also communications during docking and tracking of SOC from the orbiter must be provided (neither requirement is addressed).

Anti-jam capability and spoofing protection for communications link are not provided as required.

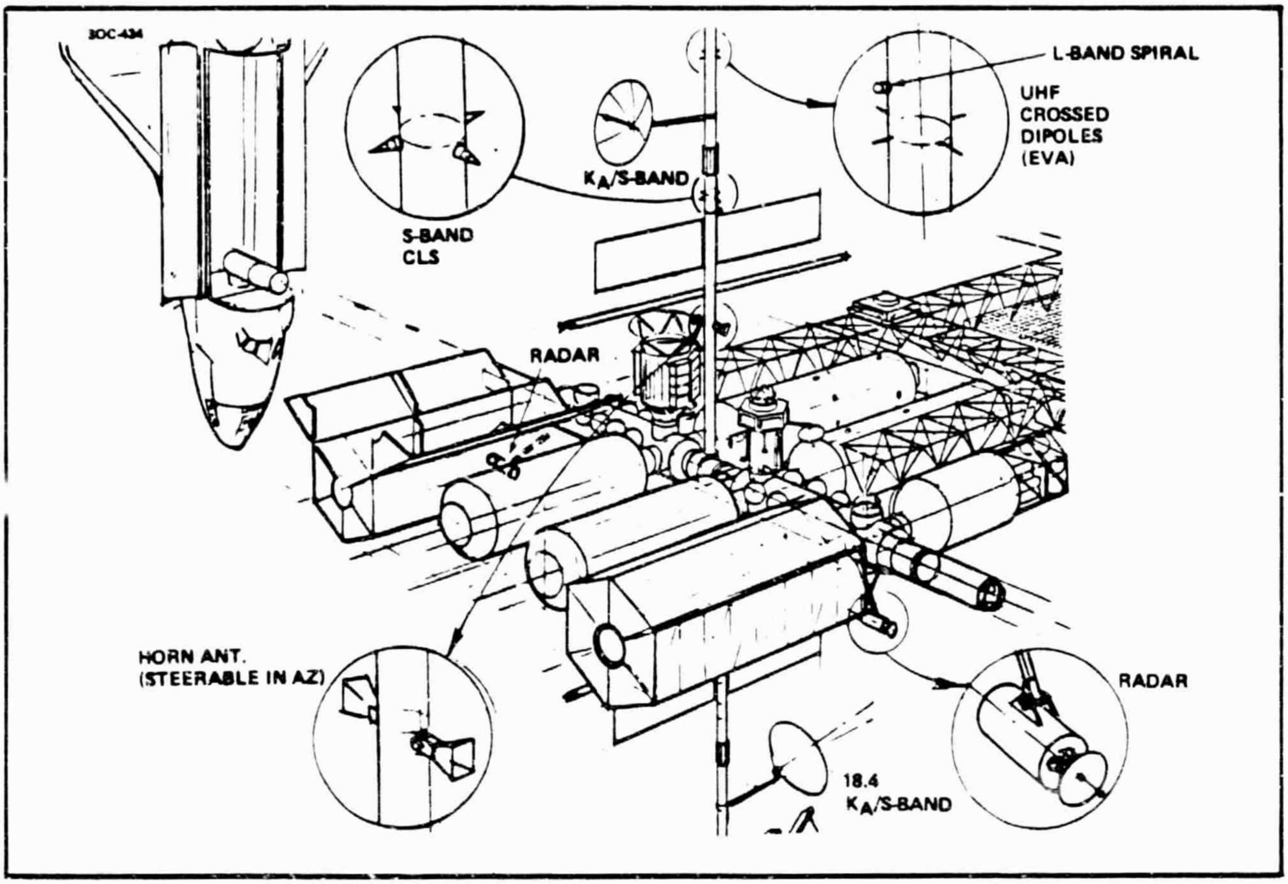

Figure 2.4-2. Space Operations Center Antenna Locations

Communications security (encryption) is provided for some links, but not all.

The following capabilities are required for SOC internal communications but are not discussed in D180-26495-3:

Public address
Wireless voicecomm
Voice access from all pressurized volumes
Communications inside airlocks and docking ports
Built-in test and fault isolation

Further definition of the tracking radar is needed in order to determine if the requirements are being met.

In summary, there are several areas in which the subsystem design does not meet the requirements. These discrepancies must be resolved either by modifying the conceptual design

or by changing the requirements, or both. There are several other areas in which further delineation of the design is needed to determine if the requirements can be met.

Major changes in the communications and tracking requirements due to the reference document 2 are summarized below.

a. Implementation is defined in three growth increments. By the final increment, all signal processing shall be digital, including voice and video signals, with selected links encrypted.

b. Hardware is required to be modularized, with separate modules for baseband, IF and RF functions.

c. Duplex TV is required for EVA.

d. The goal shall be to provide GPS navigation for all interoperating vehicles, with each vehicle continually transmitting its GPS navigation solution to SOC.

e. Tracking accuracy requirements have been loosened somewhat. The long range accuracy applies to augmented vehicles. Accuracy requirements for docking and rendezvous sensors are given.

f. The requirements for SOC-OTV communications at ranges of 400 KM and 38,000 KM have been deleted. Only the 2000 KM range is now required. However, return link TV is required at 2000 KM range, in addition to the communication channels. (The range for TV was previously 100 KM.)

g. Duplex TV is required to/from manned OTV's at a range of 2000 KM.

h. Return link TV is required from free-flyers at a range of 2000 KM.

i. The ,wing additional types of communications traffic are required through the satellite to ground:
   Teleprocessing
   Text and graphics
   Duplex TV
   Tracking

Also, separate relay satellite access from the SOC energy section is required, including command, telemetry and tracking.

j. Reference is made to a tracking and data acquisition satellite (TDAS) which could be available to supersede TDRSS in the mid 1990's.

k. No requirement for direct-to-ground communications is given.

l. Bit error rates and signal-to-noise ratios are specified for all internal and external communications.

m. The frequency bands specified previously for the various communication and tracking functions are no longer called out.

Figure 2.4-3 summarizes compliance of the proposed SOC (as defined in NASA Contractor Report No. 160944) relative to the referenced requirements.

ITEM	COMPLIANCE
A	The requirement for implementation in three increments is not addressed. All links are digitized, but not all are encrypted.
B	Not compliant.
C	Not compliant.
D	Not compliant.
E	Tracking accuracies are not addressed.
F	Not compliant.
G	Not compliant.
H	Not compliant.
I	Separate relay access from the energy section is not provided.
J	Operation with TDAS is not addressed.
K	Direct-to-ground communications is provided but no longer required.
L	Not addressed.
M	The previously specified band requirements are met, but no longer apply.

Figure 2.4-3. Compliance Summary

5.0 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SUBSYSTEM

5.1 INTRODUCTION

Both Hamilton Standard and Life Systems, Inc. were subcontractors to perform environmental control and life support subsystem (ECLS) analyses. Summaries of their results are given in section 5.2 for Hamilton Standard, and in section 5.3 for Life Systems, Inc. Figures 2.5-1 and 2.5-2 summarize the hardware recommendations made by each subcontractor. The complete reports from these subcontractors are included in the Volume 7-4 data book.

ECLSS Functions and Functional Subsystems	Initial Station Hardware	Final Station Added Hardware	Potential Candidates
Air Revitalization System			
CO_2 Concentration – Regenerable	X		SAND/EDC
CO_2 Reduction		X	Sabatier (CH4) Reactor
O_2 Generation		X	Solid Polymer Electrolysis/Static Feed Elect/Circulating Electrolyte Elect
Trace Contaminant Control	X		High Temp Catalytic Oxidizer
Atmosphere Monitoring	X		Mass Spectrometer
Atmosphere Pressure & Composition Control			
O_2 Storage – Emergency	X		High Pressure Gas
N_2 Storage – Emergency	X		High Pressure Gas
N_2 Supply	X		Cryogen/High Pressure Gas
Composition Control Monitor	X		Shuttle Derived Technology
Pressure Control	X		Shuttle Derived Technology
Cabin Temperature & Humidity Control			
Temperature Control H/I	X		Stainless Steel Plate Fin
Humidity Control H/I	X		Stainless Steel Plate Fin With Slurper
Ventilation Circulation	X		Ventilation Fan
Heat Transport & Rejection			
Water Circulation	X		Shuttle Derived Technology
External Heat Transport	X		Shuttle Derived Technology/Heat Pipe Thermal Bus
Interface Heat Transport	X		Shuttle Derived Technology/Water to Heat Pipe H/K
Radiator	X		Heat Pipe Radiator/Pumped Freon Loop
Water Reclamation System			
Pretreatment		X	Chromium Trioxide & H_2SO_4/Ozone & H_2SO_1
Water Recovery, Urine		X	TIMES/VCD
Water Recovery, Condensate & Hygiene		X	TIMES/Ultrafiltration
Post-Treatment		X	Activated Charcoal
Water Quality Monitoring		X	Total Organic Carbon, ph Conductivity
Biocide Addition & Monitoring		X	IE Addition
Microorganism Monitoring		X	TBD (IF Needed)
Water Storage	X		Stainless Steel Metal Bellows Tanks
Personal Hygiene & Waste Management			
Hygiene			
Cold	X		Stainless Steel H/X
Hot	X		Electric Heater/Shuttle Technology
Handwash	X		Shuttle Technology
Full Body Shower		X	Enclosed Stall With Handheld Spray & Directing Airflow
Laundry (Washer/Dryer)		X	Spin, Tumble Wash, Tumble Air Dry
Waste Management			
Toilet	X		Shuttle Derived Technology
Urinal	X		Shuttle Derived Technology
Solids Collection	X		Stainless Steel Recepticles With Freezing Elements/De-orbit Recepticle Bags
Trash Compaction	X		Mechanical Compactor
Compacted Solids Storage	X		Storage Bags With Biocide/De-orbit Recepticle Bags
Concentrated Waste Liquid Storage		X	Stainless Steel Recepticles With Freezing Elements/De-orbit Recepticle Bags

Figure 2.5-1 EC/LS Hardware Recommendations from Hamilton Standard

ECLSS Functions & Functional Subsystems	Recommended Baseline Approach [a]	Alternative Technology [a]
Air Revitalization System [b]		
CO_2 Concentration	*Electrochemical CO_2 Concentrator*	*Steam Desorbed IR-45 Amine*
CO_2 Reduction	*Sabatier (CH_4) Reactor*	*Bosch (Carbon) Reactor*
O_2 Generation	*Static Feed, Water Electrolysis*	*Acid Electrolyte, Water Electrolysis*
Trace Contaminant Control	*High Temp Cat Oxidizer, Regen Carbon*	*High Temp Cat Oxidizer, Expendable Carbon*
Atmosphere Monitoring	*Mass Spectrometer*	None
Atmosphere Pressure & Composition Control [c]		
O_2 Storage	High Pressure Gas	Cryogenic
N_2 Storage	High Pressure Gas	Cryogenic
N_2 Generation	*Catalytic N_2H_4 Decomposition*	Cryogenic
Composition Control/Monitor	Shuttle Technology	None
Pressure Control	Shuttle Technology	None
Cabin Temperature & Humidity Control		
Temperature Control	Stainless Steel Plate Fin.	None
Humidity Control	Stainless Steel Plate Fin., Slurper	None
Ventilation Circulation	Ventilation Fans	None
Water Reclamation System		
Pretreatment	*Ozone with H_2SO_4*	*Biopal, Antifoam & H_2SO_4*
Water Recovery, Urine	*Vapor Compression Distillation*	*Thermoelectric Membrane*
Water Recovery, Condensate & Hygiene	*Ultrafiltration*	*Reverse Osmosis*
Post-Treatment	Activated Charcoal	*UV Enhanced O_3 Oxidation*
Water Quality Monitoring	*Electrochemical Organic Content, pH, Cond*	*Total Organic Carbon, pH, Conductivity*
Biocide Addition & Monitoring	*I_2 Injection*	*Steam Sterilization*
Microorganism Monitoring	*I_2 (Biocide) Spectrophometric Monitoring*	*Microorganism Monitor*
Water Storage	Stainless Steel, Metal Bellows Tanks	None Required
Personal Hygiene & Waste Management		
Hygiene		
Cold	Stainless Steel Cooler	None Required
Hot	Cartridge Type Electric Heater	None Required
Handwash	Covered Spray & Air Transport	None Required
Full Body Shower	*Enclosed Stall & Handheld Spray*	None Required
Laundry (Washer/Dryer)	*Spin, Tumble Wash/Tumble Air Dry*	None Required
Waste Management		
Toilet	Modified Shuttle Commode	None Required
Urinal	Shuttle Technology	None Required
Solids Collection	Stainless Steel Receptacles	None Required
Trash Compaction	*Mechanical Shredding/Grinding*	None Required
Compacted Solids Storage	Stainless Steel	*Super Critical Wet Oxidation*
Concentrated Waste Liquid Storage	Stainless Steel, Metal Bellows	*Super Critical Wet Oxidation*
Habitability Provisions [d]	— Part of Another Space Station System —	

(a) All new technology is in italics.
(b) The Independent/Portable Air Revitalization System is not shown.
(c) The airlock pump, dump and relief, and pump down accumulators can optionally be included here.
(d) Part of the Habitability and Crew Support System is not included here.

Figure 2.5-2 EC/LS Hardware Recommendations from Life Systems Inc.

5.2 HAMILTON STANDARD ETCLS ANALYSIS SUMMARY

The Environmental Thermal Control and Life Support (ETCLS) activity conducted by the Hamilton Standard Division of United Technologies Corporation addressed two major tasks: ETCLS Subsystem Design and Analysis, and EVA Analysis Support. These tasks are summarized in this section. A detailed presentation of this material has been incorporated in Volume 7 of this report including ETCLS and EVA system schematics, sizes, weights, interfaces and descriptions.

5.2.1 ETCLS Subsystem Design and Analysis

ETCLS recommendations has been tailored to the Boeing approach to growth and buildup of the Space Station architecture and capability. The high inclination, incremental design (see Architecture Options) was used as a vehicle for testing ECLS integration. An initial three (3)

man free-flying station capability is characterized by open (ground resupplied) oxygen and water loops. Non-venting is achieved by liquifying CO_2 and freezing solid wastes. Wash water processing of condensate is provided for hand washing.

The use of the Logistics Module as a safe haven for the early station configurations is a critical feature that allows significant optimization by minimizing the amount of ETCLS hardware needed to meet redundancy requirements.

The ETCLS capability grows with the station by incorporating new subsystems in new modules and minimizing retrofitting/removal of original equipment. Closed water and oxygen loops are provided in the final station configuration. A step-by-step growth ETCLS capability is presented in Volume 7-4 of this report. The primary design drivers impacting ETCLS hardware implementaton are presented below:1.System Reliability/Redundancy: System reliability and replication must be sufficient to ensure that any degradation in function will follow the philosophy of Operational/Fail Operational (or Fail Acceptable)/Fail Safe. The need to replicate a subsystem within a given module is avoided by the use of the Logistics Module as a safe haven, the selection of only a three-man crew for the initial operational configurations and the ability to mix air between modules.

2. Safe Haven: The Logistics Module (LM) is designed as a Safe Haven in the Initiation Station phases, with independent ETCLS capability. This feature has a profound effect upon vehicle architecture. Because of this capability, the other two modules in the Initial Station configuration are equipped with single ETCLS systems. Any failure of one function, subsystem, or module still leaves two operating modules and ETCLS systems.

   It is implicit in this approach that there be process airflow between modules. With this, a module can remain habitable even if its air revitalization system is inoperable because CO_2, humidity and trace contaminant removal can be accomplished through interchange of air with a module whose systems are functioning. Water interchange between modules is handled in a similar fashion.

   In order to minimize recurring LM launch weight penalties, the Safe Haven is configured so that the emergency CO_2/humidity removal and O_2 and N_2 supplies are kept on the station. Bulkhead connections supply the LM with O_2 and N_2 and allow air flow through the emergency CO_2/humidity removal unit. Given the relatively low level of power consumption and heat production that will be characteristics of the LM in the Safe Haven mode, passive heat removal will be adequate to maintain internal temperature within acceptable limits.

3. ETCLS Module Size: Given the redundancy philosophy as outlined above, and the fact that the station ETCLS is required to support a crew of only three until all eight separate modules are in place, the size (or man-rating) of each ETCLS module can be optimized. Since every subsequent module attached to the Initial Station adds redundant ETCLS equipment, each of the ETCLS subsystems can be designed for a 3 man rating. There will be adequate redundancy, in the Final Station, in the event of the loss of a vehicle module plus the additional loss of any ETCLS subsystem in a remaining module, to sustain a crew of eight for up to 90 days with the station remaining in a functionally operational mode.

4. Loss Of A Pressurized Module: The vehicle architecture is designed so that, for the Final Station configuration, the loss of one pressurized volume cannot isolate the crew in a volume (or volumes) which does not have sufficient life support subsystems to allow the continuation of the mission for up to 90 days. With the requirement that the vehicle must remain operational with the loss of one module, and the fact that the Final Station uses a "racetrack" design, the crew still has access to and use of seven of the eight modules. Degradation in crew amenities (for example, loss of the one module which contains the shower) is allowable for the duration of the crew cycle period.

5. Water Management Evolution: The requirement for minimum water amenities (handwash and sponge bathing) on the Initial Station eliminates the need for sophisticated hygiene water processing since handwash can be supplied through the filtration of condensate. With this philosophy, water processing, and the amenities associated with having it (showers, clotheswash) can be developed for later add-on modules and be tested as in-flight experiments when these modules are attached to the station. They will then be certified when the Final Station becomes operational.

6. No Venting: The only gases permited for venting from the station are hydrogen and methane. Since dumping of crew metabolic CO_2 is not allowed except in an emergency, CO_2 will be liquified and stored in LM tanks for return to earth during Initial Station phases. In the Final Station configuration, with closed loop ETCLS operation, the CO_2 will be reduced to methane which is incorporated into a resistojet RCS and to water which is reclaimed. Additionally, the use of an electrolysis/fuel cell to reconstitute potable water eliminates any concern for contaminant carry-over.

7. Waste Management: The elimination of venting has a significant impact on existing feces processing technology. The present Shuttle solid waste management system vents water vapor overboard as it vacuum dries the biowastes to a stable storage condition. The most

attractive alternate to eliminate venting is frozen storage. The system could be similar to the present design except that a cooling unit, perhaps a thermoelectric design, would be used to maintain all feces solids and liquid in a frozen state, at a penalty of approximately 20 watts continuous power per man.

Another, quite different option, would employ the use of waste bags for all vehicle wastes and periodically de-orbit these bags to burn up on reentry. The concept, untested to date, would require the development of a waste bag which could be pumped down to 0.5 psia and maintain integrity storage volume requirements and could eliminate the need for trash compaction and biological stabilization.

5.2.2 EMU/EVA System Considerations

The Extravehicular Mobility Unit (EMU) design selected for a Space Station will be driven by the requirements and objectives of the station.

The two major drivers affecting EMU design are: 1) Vehicle contamination concerns, and 2) Forecasted frequency of extravehicular activity (EVA's).

1. <u>Vehicle Contamination Concerns</u>: In order to prevent contamination on or interfere with vehicle or payload external surfaces (mirrors, sensors, windows, etc.), there will most likely be a requirement that no gases can be vented which could condense and freeze on surfaces.

   The current EMU, designed for use on Space Shuttle missions, utilizes a water sublimation thermal control subsystem for heat rejection. It uses approximately 12 pounds of water per 7 hour EVA. This water would be vented directly into the local environment of the vehicle, thereby raising the potential for ice formation on surfaces or the buildup of a vapor cloud surrounding the vehicle.

   One potential concept under consideration to eliminate venting is a hybrid radiator-thermal storage system. With this concept, the backpack radiator is the primary means of rejecting the crewman/PLSS heat load. If he is working at elevated heat output levels, or if he is in an area where the radiator capability is diminished, the thermal storage unit will act as a supplemental heat sink. The thermal storage unit will employ a phase change material (e.g. ice/water) which will melt during absorption of crewman heat. The material will be resolidified in the vehicle between EVA's at a power penalty of 1.8 kw-hours per EVA.

This regenerative, non-venting system will require initial (one time) launch penalties of 100 pounds and 1.2 ft^3 per unit. The vehicle regenerating station will also weigh approximately 100 pounds and require 1.2 ft^3 of volume.

2. <u>EVA Frequency</u>: Frequency of EVA's may be the determining factor in the decision as to whether the Shuttle EMU is adequate for Space Station usage or whether modifications and improvements are necessary. The key aspects of frequency of EVA affecting EMU design are as follows:

   a. <u>Expendables Penalty</u>: The present EMU requires approximately 12 pounds of water for thermal control per 7 hour EVA. Contaminant/CO_2 control is presently accomplished by an expendable LiOH cartridge, at a penalty of 6.4 pounds per EVA.

   If Space Station EVA frequency is projected to be very low (80 per year), which may be the case for a station whose main function is Science and Applications, these expendable penalties may be acceptable.

   If however, the mission model projects higher EVA frequencies (1200 per year) as expected with construction and satellite servicing missions, it is cost effective to design completely regenerable thermal and contaminant control systems.

   The major elements of a regenerable Portable Life Support System (PLSS) for the EMU will be: 1) regenerable thermal storage unit, and defined above, 2) regenerable contaminant/CO_2 removal unit; and, 3) Long life (100+ recharges) battery.

   The regenerable CO_2 removal system could be any one of several promising concepts--solid amine, membrane diffusion, electrochemical depolarizer (EDC), or metal oxides. Any of these systems should weigh less than 50 pounds and occupy less than 0.6 ft^3. The recharge power required to regenerate the CO_2 removal system will be approximately 2.4 kw-hours.

   The present EMU silver-zinc battery, can only be recharged 8 times. Potential alternatives with greater recharge capability are Ni-H_2 batteries and small fuel cells. Both of these concepts have yet to be quantified, but either could offer substantial resupply savings for mission scenarios calling for frequent EVA's.

b. EMU Suit Pressure: In order to avoid uncontrolled loss of body tissue nitrogen (the "bends"), an EVA crew member must either prebreath pure oxygen at ambient pressure for approximately three hours prior to EVA or his EMU operating pressure must be high enough that a ratio of cabin N_2 pressure to the EMU pressure is less than or equal to 1.6. For a 14.7 psi or 10.2 psi Space Station operating pressure, the required EMU pressure to avoid or minimize prebreath would be 8 psi or 4.3 psi, respectively.

If the station forecasted EVA frequency is low (80 per year, i.e., less than 2 per week) the added crew time required to perform prebreath may be acceptable, hence the present suit pressure would be adequate for a 14.7 psia cabin pressure.

However, if the mission model calls for daily routine EVA's, prebreathing is unacceptable and, if the station is to be operated at 14.7 psia, an 8 psi EMU is required. For this combination of pressures, the station maximum 0_2 concentration of 25.9 percent maximum can be used (desirable from a material flammability standpoint), immediate EVA egress is possible and compatibility with the Shuttle is maintained.

However, an 8 psi EMU operating with 100 percent pure 0_2 could present long term oxygen toxicity problems for a crewmember performing daily EVA's. Conclusive data does not exist concerning this subject, yet the oxygen toxicity fear may be eliminated by providing a two-gas (0_2 & N_2) 8 psi EMU system. By utilizing the partial pressure of N_2 which exists within the EMU prior to donning, a crewmember can "precondition" the EMU such that gradual 0_2 partial pressure concentration is controlled and oxygen toxicity problems associated with pure 0_2 checked.

5.3 LIFE SYSTEMS, INC. ECLSS ANALYSIS SUMMARY

Under the present Contract Life Systems, Inc. investigated the Environmental Control and Life Support Systems (ECLSS) for a Space Station. The purpose was to begin establishing the state of ECLSS technology and its relationship to projected Space Station missions.

5.3.1 Analysis

The primary task assigned to Life Systems, Inc. was to provide technology inputs on the Air Revitalization System (ARS) and Water Recovery System (WRS) of an ECLSS for a Space

Station whose architecture and mission is still in an evolutionary stage.

The results of the studies indicated closed-loop ECLSS will provide a tremendous cost savings (over $100 million) to NASA. Also, the technology that would be used will not inhibit known Space Station missions. Further, the use of an automated, closed-loop ECLSS will allow for a higher crew productivity and decreased costs associated with expendables replacement.

In completing its program, Life System offered a number of recommendations. These were screened and condensed into a few considered having higher priority.

5.3.2 Recommendations

The following is a list of the more important program generated recommendations:

1. An open loop should not be recommended for any stage of a Space Station evaluation. The loop should be closed in the sequence CO_2 removal, water recovery and O_2 recovery closure might be considered a candidate for being included at the "scarring" level only, on the initial station.

2. NASA should start immediately expending its efforts to integrate subsystems into systems for at least two of the five major ECLSS: Air Revitalization System and Water Recovery System.

3. NASA should improve its method of planning ECLSS developments. Appendix 1* contains a summary of a draft plan prepared for NASA in April, 1980. The current budget is inadequate to provide developed technology for a flight program (unless development is carried out on the flight program, which is an expensive alternative). The schedule is getting very tight for having all the needed technology ready for a 1986 Phase A/B initiation and a 1992 launch.

*Appendicies are found in Volume 7-4.

4. NASA should raise its funding of Space Station ECLSS developments from the $2,000,000 in 1982 to:

Fiscal Year	SRAT Funding ($000)
1983	4,000
1984	7,000
1985	10,200
1986	12,400
1987	20,000
1988	25,000
1989	24,300
1990	21,700
1991	18,000
1992	17,000
Ten Year Total	$160,000

This will result in mature advanced life support technology ready for a flight program with minimum development risk (i.e., as was characteristic of the Shuttle program).

5. NASA should allocate the above (item 4) space research and technology funding into the following Technology Categories in the percentages shown:

Technology Category	% of Budget
Flight Technology Demmonstrations	20
Systems Developments	23
Subsystems Developments	16
Component Maturity and Concept Developments	14
LSS Engineering Analyses[(a)]	4
Basic and Applied Research	6
Unspecified	17
Total	100

Note, a significant (17%) is set aside for the unexpected characteristics of R&D efforts. Also, 6% focused on basic and applied research. Over 80% of the later should be on the applied research portion.

6. Many technology gaps exist in a fully regenerable or Spaçe Station applicable ECLSS because the ECLSS funding has decreased considerably (see Appendix 2).* These include development of such items as:

   a. Components, e.g.,
      1. A trash compactor
      2. A whole body shower
      3. A gas chromatograph/mass spectrometer atmospheric analyzer
      4. A water quality monitor
      5. A reliable O_2 sensor
      6. A dish/clothes washer/dryer
      7. A purge pump for phase change water recovery system

   b. Subsystems, e.g.,
      1. A Bosch-type CO_2 Reduction Subsystem
      2. A Hyperfiltration Subsystem
      3. A Nitrogen Supply Subsystem

   c. Subsystem Integrations, e.g.,
      1. Water Recovery System, Four-Person
      2. Air Revitalization System, Four-Person
      3. Waste Management System, Four-Person

   d. A flght technology demonstration program to prove the technology is ready/mature, e.g.,
      1. Air Revitalization System (Sabatier based)
      2. Water Recovery Sysem (VCDS based)

   e. A test bed program whereby modular ECLSS is assembled. It should allow for verifying alternative approaches and operated with a high level of automation. It should allow testing with humans.

*Appendices found in Volume 7-4

f. A component endurance (and characterization) test program e.g.,

1. Various mechanical integrations such as 3-Fluids Pressure C ntroller of the water electrolysis subsystem
2. CO_2 concentration module
3. Steam Desorption CO_2 removal bed
4. Water electrolysis module
5. Etc.

The goal should be 40,000 hours of testing with exposure to operating temperature, pressures, flows, etc.

7. NASA should raise the awareness level to the importance maintainability will have on the practicality of the Space Station mission. This requires development efforts and specific demonstrations not only noting maintenance will be needed to meet the Space Station mission lifetime requirement.

8. Consideration should be given to integrating the Air Revitalization System's water electrolysis subsystem requirements with those of the regenerative fuel cell system.

9. The following should be considered Space Station utilities:

   a. Power/electricity
   b. Coolant
   c. Nitrogen
   d. Water (hot and cold)
   e. Communications (bus)
   f. Hydrogen
   g. Oxygen

   The first three or four are typical. The last two or three are not but offer some major advantages as Rockwell pointed out in their Modular Space Station studies.

10. More . me will be spent on evaluating cost effective levels of redundancy for life support functions aboard the Space Station. The Space Operations Center, for example, incorporated considerably more CO_2 concentrators than was warranted.

(a) North American Rockwell, "Modular Space Station, Phase B Extension," Preliminary System Design, NAS9-9953; January, 1972.

6.0 MANIPULATOR SUBSYSTEM

6.1 INTRODUCTION

SPAR Aerospace, Ltd., was engaged to provide information on the shuttle RMS capabilities and characteristics, potential RMS improvements, RMS space maintainability considerations, manipulator simulation and analysis development issues, and mobile RMS concepts. This section gives a summary of the results of their analysis. The full write-up is included in Volume 7-4.

6.2 SUMMARY OF RESULTS

6.2.1 Shuttle RMS Capabilities and Characteristics

A condensed overview of the RMS system was provided.

6.2.2 Potential Improvements in Shuttle RMS

The present shuttle RMS design has been primarily governed by considerations of payload retrieval and deployment from the orbiter. A number of improvements of the RMS can be envisaged to expand its capabilities in performing tasks related to satellite servicing and module interchange, inspection, space construction, materials handling and transfers, etc. Such tasks are likely to be routinely performed on a space station.

The improvements can be broadly divided into the following categories:

a. improved ability to do precise tasks
b. improved operator control aimed at reducing operator effort and/or work load
c. increased reach and articulation

The items that can be considered are discussed below. The needs and priorities of the RMS application would determine which of these items should be considered for a space station.

<u>Force/Moment Sensing & Feedback</u> - The present RMS has no provisions for sensing the force and moments at the end-effector/payload interface, although the maximum level of the forces/moments can be adjusted by setting the motor current limits in the joints at the required values. Knowledge of forces and moments at the arm tip may be very helpful to the operator in

performing tasks involving constrained motion of the payload. A force/moment sensing & feedback system for SRMS has been under development at SPAR Aerospace and data was provided.

Force/Moment Accommodation - The concept of force accommodation is basically a software enhancement once the force/moment sensing and feedback are in place. A concept was presented.

Visual Proximity Sensing - The shuttle RMS provides CCTV views from wrist camera (and elbow camera, if attached to the arm) to the operator who can use these views to judge relative distance, orientation and rates, between the arm tip (end-effector) and the payload that he/she is trying to capture. A real-time photogrammetric system (RPS) can use the TV view to determine precisely the distance, orientation and rates between the end-effector and a payload. Such a system has been developed by NRCC and Leigh Instruments in Canada and has been demonstrated at the Manipulator Development Facility (MDF) at NASA JSC. This system was described.

Stand-alone Computer System - The SRMS uses the shuttle GPC as a computing resource and as a repository of SRMS software. A stand-alone computer system for the RMS would eliminate this dependance on the GPC allowing the RMS to be located as a separate system on a space station. Advantage may also be taken of the advances in VLSI technology in designing the new computer system which would be able to provide additional computing resources needed by other features such as force/moment sensing and feedback, force accommodation, photogrammetric sensing, more degrees of freedom, and collision avoidance.

Collision Avoidance Software - Limited computer resources precluded inclusion of collision avoidance function in the SRMS software to have the capability of predicting potential collisions between the arm, payload, orbiter and its contents. The collision avoidance capability can be considerd for application in Space Stations where routine RMS operations may be automated to a high degree and VLSI technology would make considerable computing resources readily available.

End-of-Arm Tools - The RMS can be used for performing functions such as activation of latches and mechanisms, attachment and detachment of modules, connection and disconnection of umbilicals, and holding objects to support space construction tasks, if suitable tools are designed for operation at the end of the arm. The tools could range in complexity and capability from using the RMS motions to active (powered) tools for shearing, impact and damping. Some concepts proposed to NASA were shown.

Voice Activated Controls & Displays - The technology of direct voice communication to and from a computer is becoming increasingly sophisticated. Such a system can be considered for RMS to reduce workload for the operator and to enable him/her to exercise more control authority over the RMS without letting go of the hand-controllers. A voice activated system could be considered for the following functions:

a. Selection of the operating mode of the RMS
b. Selection of display parameters (joint, angles, rates, etc.)
c. Some of the end-effector operations
d. Caution and warning, and to "read" the display parameters to the operator.

Control From a Payload Station (MRWS) - In some potential applications of the RMS a manned remote work station (MRWS), such as the open cherry picker, is envisaged. Such a work station would be an RMS payload. A display and control panel can be provided in the work station to operate the arm. This would be in addition to the main control panel in the RMS crew cabin. The implementation of this concept was described.

Increased Reach and Articulation - Several concepts were described.

6.2.3 Space - Maintainability Considerations for RMS

The shuttle remote manipulator system hardware Line Replacement Units (LRU's) and Shop Replaceable Units (SRU's) were described. The present categorization of hardware could be maintained for an RMS for the Space Station. The manipulator arm LRU's would be handled by EVA. Two or more astronauts may be needed to remove or install LRU's with appropriate handling aids, tethers and tools. Some of the interfaces may have to be re-designed to enable mechanical connections (bolts, clamps, etc) and electrical connections to be made quickly by an astronaut in a spacesuit with suitable tools.

The LRU's could be brought into an enclosed, pressurized service bay in the Space Station to act as a shop where LRU's could be serviced and SRU's replaced. Some design changes may again be required to modify physical interfaces for zero-g assembly and disassembly with appropriate tools and handling aids.

In-orbit fault detection and isolation procedures would also have to be developed to support the maintenance activities. Trade-off's involving on-orbit servicing versus ground-servicing also would have to be carried out.

6.2.4 Manipulator Development Issues: Simulation & Analysis

The current RMS analysis and simulation activities were described. Simulation and Analysis would be needed for development of manipulators for a space station in the following phases:

a. Requirements definition. Analysis and Simulation could be used to support space station manipulator operations analysis and manipulator tasks. SIMFAC and ADAD, with appropriate changes, could be used to study shuttle-RMS type manipulators and their operations for anticipated tasks. Such activities would lead to definition of requirements for space station manipulators.

b. Design and Development. The analysis and simulation effort needed would depend on the manipulator concept selected to meet the requirements. It may be possible to use ASAD and SIMFAC with small modifications, or new simulations may be developed based on the experience and expertise gained in the shuttle RMS simulations.

c. Verification & Training. The role of simulations to verify operational scenarios and to train the operators would be similar to those for the shuttle. Some training may be conducted in orbit on the space station.

6.2.5 RMS Track and Base Assembly Concept for a Space Station

Boeing Space Station concepts at present have a shuttle RMS type manipulator(s) mounted on a linear track. This increases the operating envelope of the manipulator. Payload handling operations would involve translation of the RMS, carrying a payload, along the tracks.

Such a system would require a track system, a drive system and an interface structure between the RMS and the track/drive assembly. The main operational requirements for the system were defined and concept for the track, base, and drive system were defined.

7.0 RESUPPLY CONSIDERATIONS

7.1 LOGISTICS MODULE REQUIREMENTS

In order to provide adequate resupply of food, water, household supplies, ECLS, propellants, and mission equipment every 90 days it was determined that at least three dedicated logistics modules would be required. One in use at the space station, one being prepared for the next resupply mission, and one backup (possibly the test article) in case of contingencies. An evolutionary module design would be required to handle the increasing resupply volume requirements as the crew sizes changes from four to eight then to twelve in the early years of the space station.

Other requirements such as ground handling and time from loading of module until delivery to the space station has a large impact on the design. The design needs to account for the method of maintaining freezer, refrigerator, and shelf stable areas at the appropriate temperatures. Monitoring circuits are required to alert crew members that the logistics module is approaching its allowable limits and provide a record of the internal temperatures. This record will provide assurance that the frozen refrigerated and shelf stable foods have not exceeded their allowable limits. The design also has to consider the likelihood of contamination of the module during ground handling.

Uniform package sizing or cabinet size is needed to simplify construction handling, and repackaging in space. This uniform sizing along with a positive inventory control method will make the resupply identification, handling, and location much easier on the space station. Once the logistics module is loaded a positive inventory control system is needed to identify location and quantity of supplies.

Hard attach points have been provided on the cabinet fronts to allow handling of supplies that are too bulky, long or have odd shapes. Small missions could be manifested in the logistics module using the hard points when space is available.

The design of the logistics module needs to incorporate a method of providing security for the military and commercial customers.

The military will require a secure area for carrying classified documents and equipment. Commercial customers will require a system for protecting proprietary equipment, document, and material.

In order to minimize ground handling costs, the logistics module needs to take into consideration the sizing of the various ground handling and shipping methods. To expedite shipping, from the factory or east to west coast, sizing for air transportation would be desirable. Truck or rail would be the next choice with ship or barge as the last choice in transportation.

7.2 DELIVERY REQUIREMENTS

The space station resupply requirements are shown in figure 2.7-1. This figure gives the 90-day, 4 crew member weight and volume requirements.

Item	Mass KG	Volume
Food		
Shelf Stock		
.95 KG/Person/Day	340.2	40.05
Frozen		
.45 KG/Person/Day	162	19.35
Water	121	14
ECLS		
Air Revitalization	80.64	9.1
Personal Gear		
74 KG/Person	296	5.2
Housekeeping Supplies		
Station Stores	47	3.4
Supplies/Hygiene	321	28
Maintenance-Filters	71	5.3
Spares	136	11.9
TMS**	1000	35
RCS	2200	85.8
EMU		
4 EMU's	783	88.4

*Assumes Closed Loop ECLS
**If the TMS uses hydrazine or bi-propellant figure 2.7-2

Figure 2.7-1. Resupply Requirements (Crew of 4 for 90 Days)*

The water resupply requirements are based on not cooling the EMU by evaporating water and having purification units capable of providing potable water.

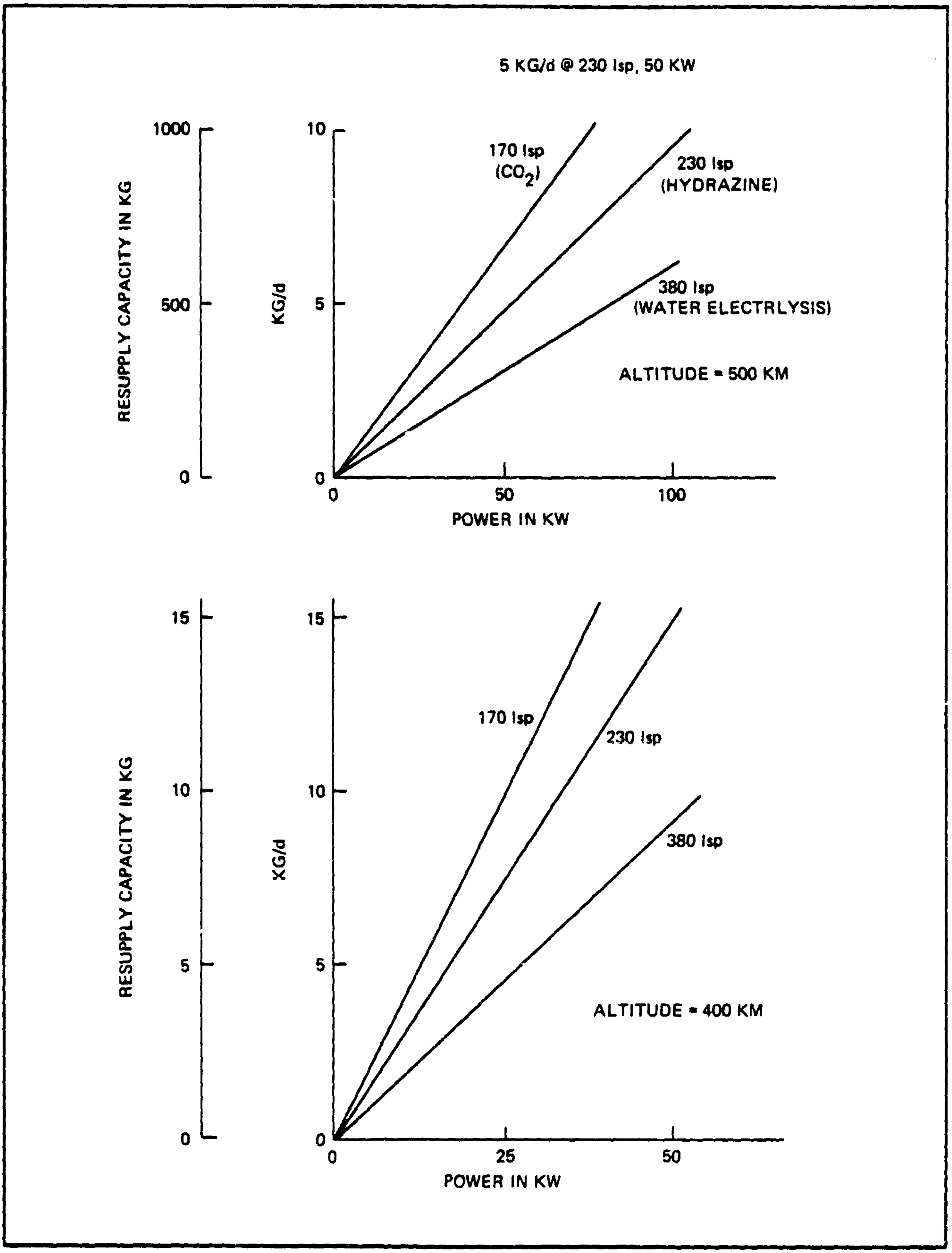

Figure 2.7-2 Propellant vs. Atmosphere vs. Altitude

7.3 LOGISTICS MODULE RETURN REQUIREMENTS

7.3.1 Waste Generation and Stowage

The logistics module will be utilized to store and return to Earth all Space Station wastes. Experience with the shuttle has resulted in the waste generation rates shown in figure 2.7-3. In plotting the volumetric storage requirements for wastes, figure 2.7-1, it is apparent that on a mission longer than 36 days a trash compactor would reduce the volume of trash considerably. The weight generated by this trash, compacted or noncompacted, shown in figure 2.7-4, is not significant compared to the resupply weight.

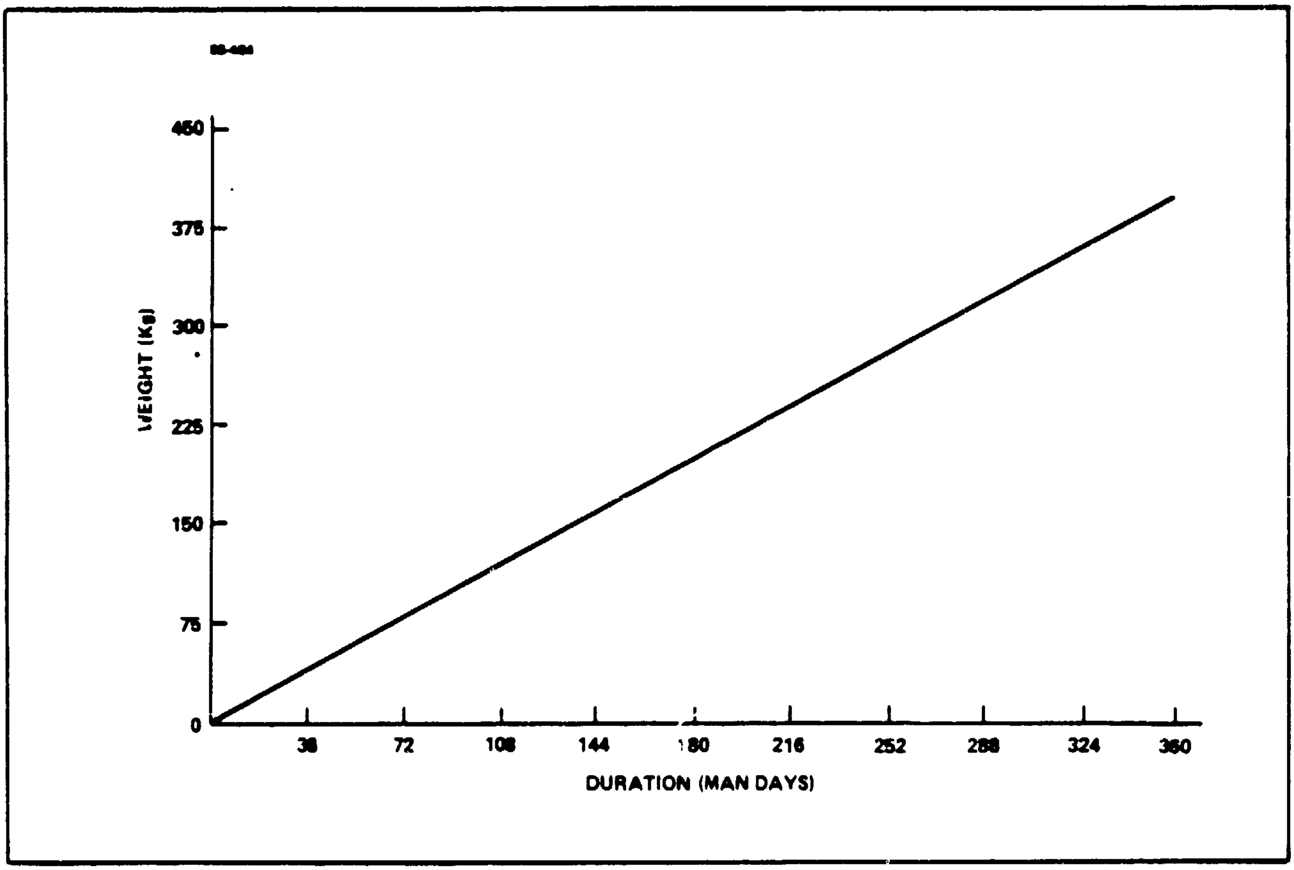

Figure 2.7-3 Waste Generation Rate

Making the compacted trash size and the logistics module storage shelf size compatible reduces the day-to-day trash handling and management tasks significantly.

The trash management and housekeeping tasks will require the use of a biocide to keep the space station free of potentially harmful organisms.

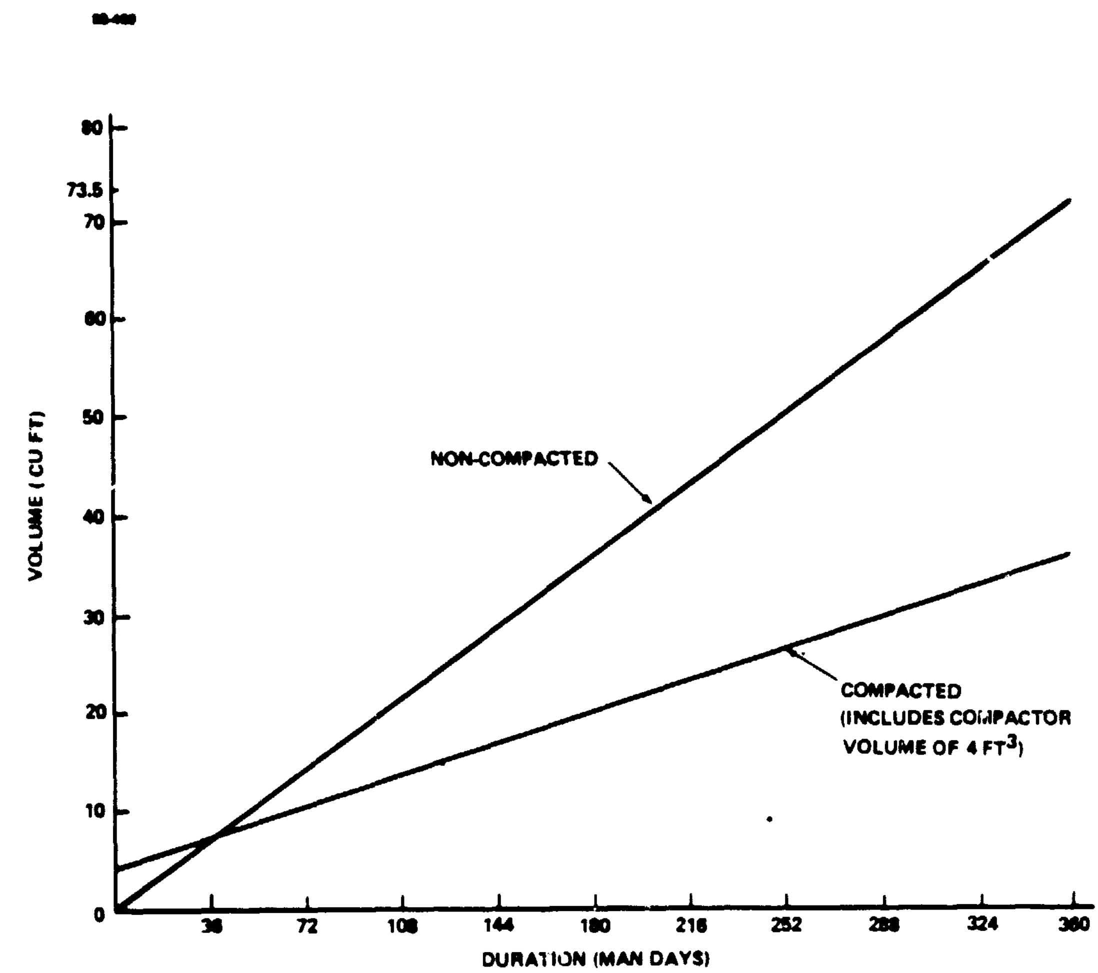

Figure 2.7-4 Volumetric Storage Requirements for Wastes

7.3.2 Mission Equipment and Products

Compacting the trash will reduce its storage requirements and provide more room in the logistics module for returning small mission equipment samples of experiments and materials and products fron. the commercial manufacturing processes.

7.4 CONFIGURATION OPTIONS

7.4.1 Configuration of Logistics Module as a Safe-Haven

The logistics module could serve as a safe-haven for four crewmembers with certain modifications. With the logistics module built in this configuration it could serve as a habitat module during the initial space station buildup phases.

In order to be used to supply the normal habitability module functions the logistics module would need the functions listed in figure 2.7-5. The subsystem sizing for these functions is

ETCLS FUNCTIONS	DEDICATED FOR SAFE-HAVEN	COMMENTS
VENTILATION SENSIBLE HEAT	X X	COMBINED FAN/HX PACKAGE
LATENT HEAT CO_2 REMOVAL ODOR/TRACE GAS REMOVAL	X X X	COMBINED FUNCTIONS PERFORMED BY HS-C PACKAGE LOCATED IN HAB. MOD.
O_2 MAKEUP N_2 MAKEUP	X X	TANKS ON HAB. MOD. WITH STANDARD 2 GAS CONTROLLER IN LOGISTICS MODULE
H_2O, FOOD & DRINK	X	HOT H_2O DISPENSER
FOOD	X	DRY FOOD KIT (FROZEN FOOD NEEDS OVEN)
COMMODE	X	REDUND. OF PLUMBING & POWER TO ASSURE AVAILABILITY
TRASH	X	21 DAYS OF CLOTHES, WIPES & FOOD CONTAINERS
CLOTHES	X	DISPOSABLE CLOTHES STORAGE IN LOG. MOD. FOR EARLY STATION
HYGIENE WIPES MEDICAL SUPPLIES	X X	KITS MOVED TO HAB. MOD. FOR LOG. MOD. SWITCH OUT & BACK TO LOG. MOD. TO SUPPORT SAFE-HAVEN

Figure 2.7-5 ETCLS Functions Needed for Safe-Haven

shown in figure 2.7-6. The ECLS Functional Requirements for using the logistics module for a safe-haven are shown in figure 2.7-7.

VEHICLE/FUNCTION	WEIGHT (LBM)	VOLUME (FT^3)	POWER (WATTS)
LOGISTICS MODULE			
SENSIBLE HX PACKAGE	50	2.5	235
O_2/N_2 CONTROL	30	1.5	60
TOTAL LOGISTICS MODULE	80	4.0	295
HABITABILITY MODULE			
N_2 TANKS (2)	226	9.5	0
O_2 TANKS (4)	488	18.9	0
H_2O TANKS (3)	638	20.3	0
HS-C PACKAGE (1)	143	8.5	80
TOTAL HABITABILITY MODULE	1495	57.2	80
TOTAL SAFE-HAVEN	1575	61.2	375

Figure 2.7-6 Subsystem Sizing for Safe-Haven

7.4.2 Growth Logistics Module Configurations

There are several methods of handling the logistics module growth requirements.

a. tailored - build individual modules to meet each crew size requirements

b. modular - build modular sections that can be added for each incremental increase in crew size

c. oversize - construct an oversized module that is too large for the first crew but is adequate for the next increase in crew size. After that, with each addition to the crew size increase the frequency of logistics module delivery flights.

7.4.3 Side Port Configuration

Providing an additional docking port on the side of the logistics module would allow easier loading, unloading, and checkout on the ground, see figure 2.7-8. At the space station it would allow another module or device to be attached temporarily to the logistics module. If a second logistics module were required for any reason, this would provide a logical port for it to use.

If a large side access hatch were provided in the logistics module, see figure 2.7-9, it would allow easier ground loading, unloading, and checkout. Once the module was loaded, the side hatch would be sealed until the module returned to earth.

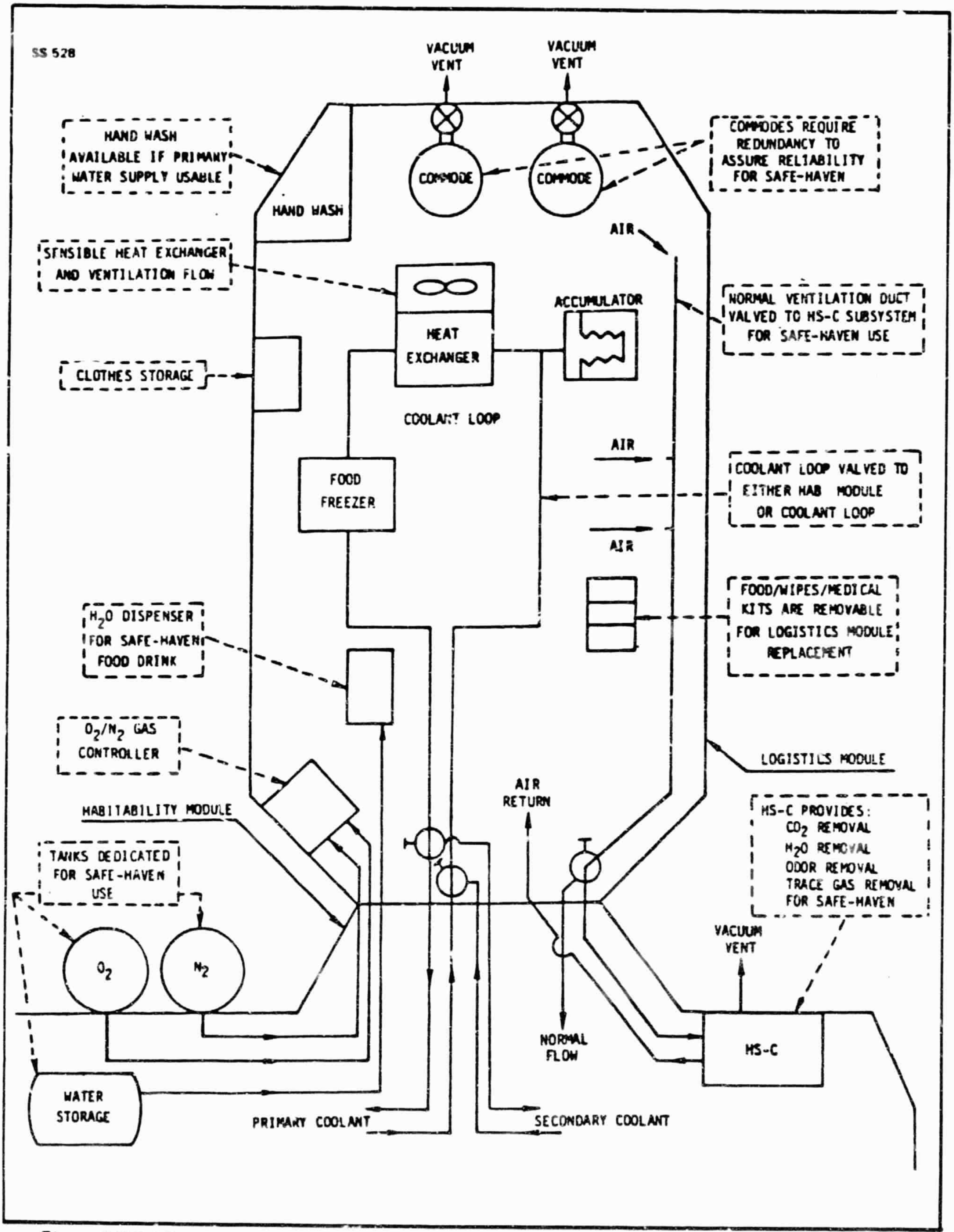

Figure 2.7-7 ETCLS Functional Requirements for Using the Logistics Module for a Safe-Haven

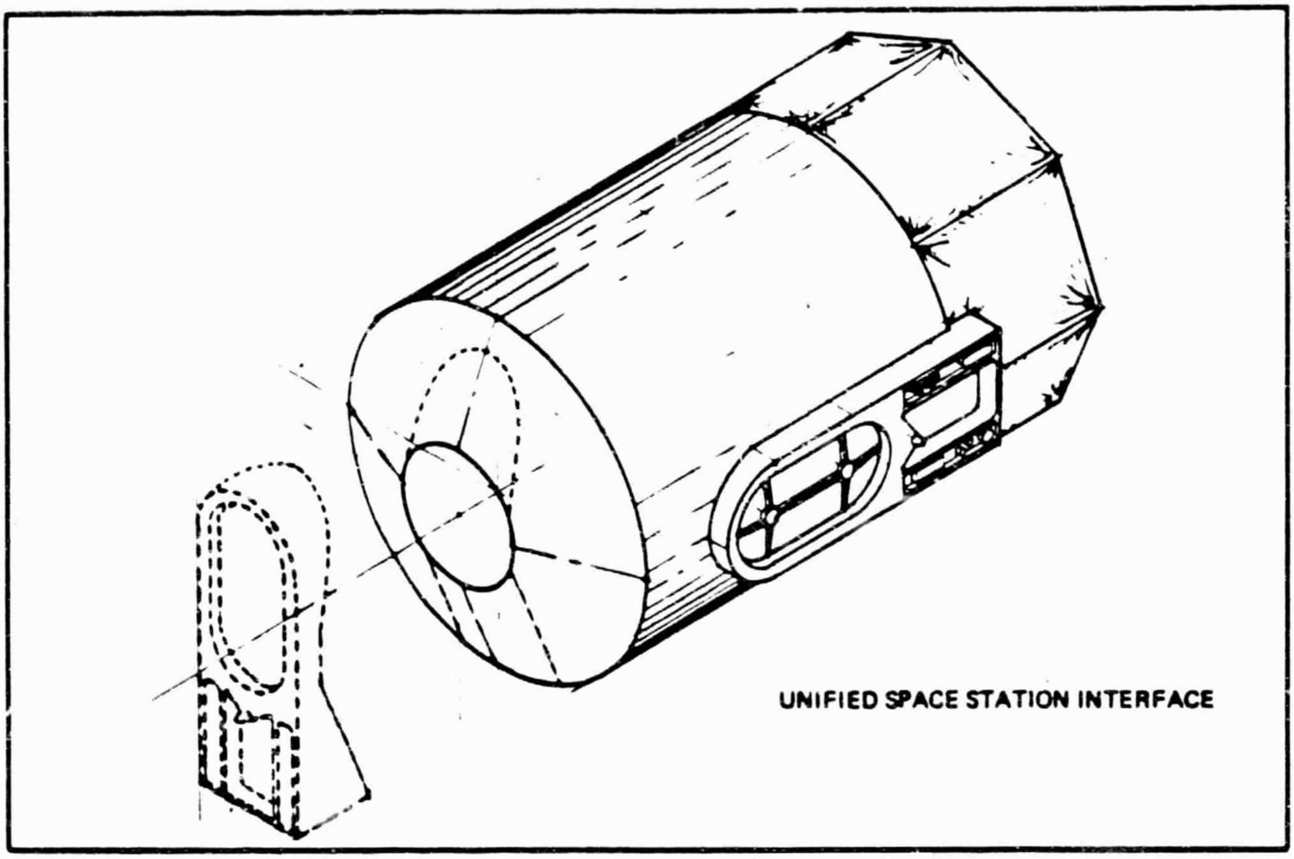

Figure 2.7-8. Logistics Vehicle with Ground Access Door

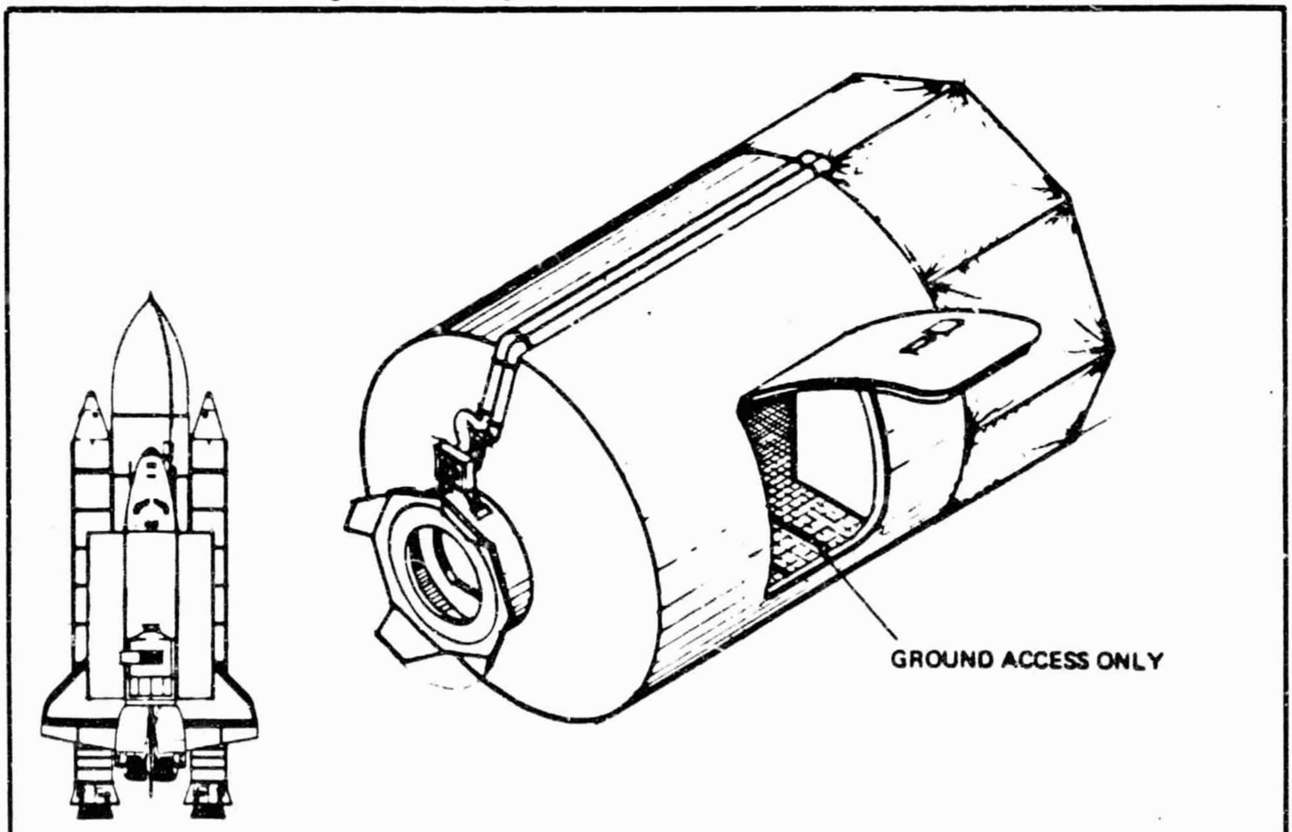

Figure 2.7-9. Logistics Vehicle with Side Loading Berthing Port

8.0 POINTING SUBSYSTEM

8.1 INTRODUCTION

Dornier provided Boeing with a data book on their experience in the development and manufacture of stabilized gimbal systems, starting with balloon borne telescope pointing systems and maritime antenna stabilization systems. In the space field the following gimbal systems have been developed by Dornier:

- the Instrument Pointing Subsystem (IPS)
- the two axes antenna pointing mechanisms for the German MRSE and MRSE-MAS
- the Position and Hold Mount (PHM) covering phase A, B and demonstration model
- the Antenna Pointing Mechanism (APM).

A detailed system description for IPS, PHM and APM is given in the Volume 7-4 Data Book. The Space Station relevant payloads were analyzed and are summarized in Section 8.2 and in the Data Book. The Space Station accommodation aspects are discussed in Section 8.3.

8.2 REQUIREMENTS SUMMARY

8.2.1 Attitude Pointing/Stability/Mass

Astrophysics

Three major groups can be identified

1. Pointing accuracy — 1 arcmin down to arcsec; high stability requirements

   Most payloads are in the range from 200 to 8000 kg, but some are heavier.

2. Pointing accuracy — in the range of 0.1 arcsec

Most payloads are in the range from 10 to 100 kg and a few up to 270 kg.

3.	Pointing accuracy	greater 1 deg
	payload mass	10 - 150 kg

Earth Remote Sensing/Environmental Observations

A broad spectrum of sensors is considered

- RF
- optical

with pointing requirements of 0.05 to 0.3 deg

Payload mass e.g. LIDAR	up to 3500 kg
RF, Optical	up to 150 - 200 kg

(one payload up to 10000 kg. but one 720 arcmin pointing accuracy)

Communications

Large antenna pointing	0.1°
Major pointing constraints	low payload eigenfrequencies

8.3 POINTING SYSTEM ACCOMMODATION ON THE SPACE STATION

8.3.1 Accommodation Analysis

The pointing stability requirements versus the mass of potential European Spacelab Experiments are summarized in Fig. 2.8-1. The mass/accuracy ranges of IPS and the PHM are indicated, a wide range of experiments can be covered by these two systems.

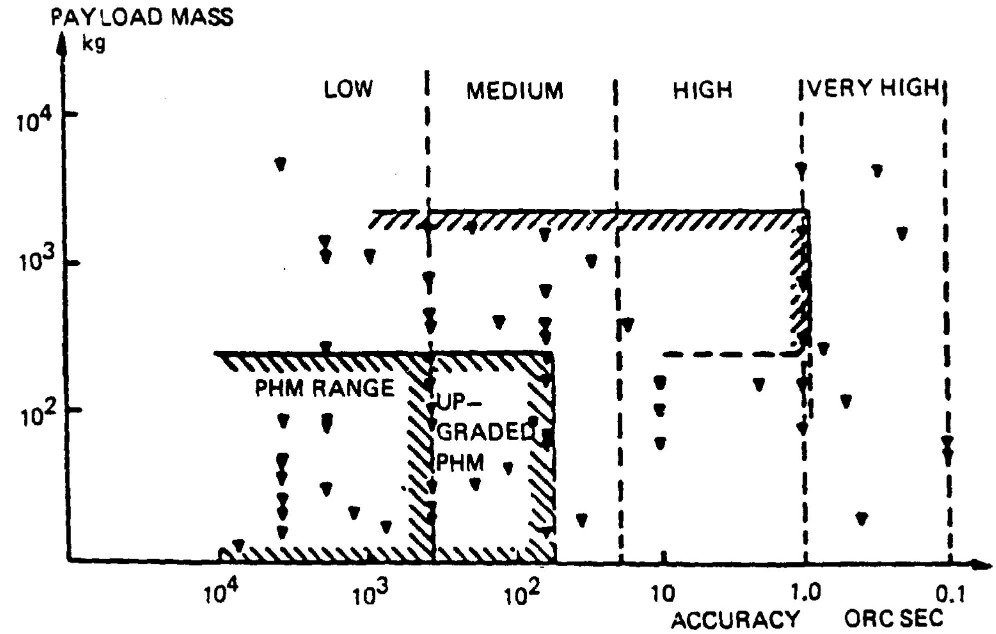

Figure 8-1 IPS and PHM Stability and Payload Range

8.3.1.1 IPS

Dynamics

- Orbiter

  o Orbiter Limit cycle — $\pm$ 0.1 deg/$\pm$ 0.01 deg/sec

  o Lowest Orbiter/Pallet Eigenfrequency — 4 Hz

  o Disturbances — Man motion; Thruster firing

- Space Station

  o Limit cycle — TBD

o Lowest Space Station Eigenfrequency	ca. 1 Hz (expected)
o Lowest eigenfrequency of Solar Array System	0.1 Hz
o Disturbances	- Man motion - Distributed actuators (e.g. thrusters) - RVD activities - Moved parts (RMS etc.)

Rigid body angular accelerations of the Space Station due to disturbances and attitude control are expected to be lower in amplitude and frequency.

The disturbances are depending on

a. rigid body rates and angular accelerations

b. distance of IPS mounting location from Space Station C.O.M.

c. local translatorial accelerations and angular deflections due to Space Station flexibility.

<u>to a)</u>

Rigid body rates and angular accelerations are expected to be much lower than for the STS due to the Space Station high moments of inertia.

<u>to b)</u>

IPS performance simulations have been executed with a distance of about 1.6 m from C.O.M. For the Space Station a distance up to 10 - 15 m seems to be more realistic. Great attention has to be payed to the fact that resultant disturbances (lower rates, angular accelerations but much greater distances) are in compliance with the IPS-torquer capabilities (30 Nm).

<u>to c)</u>

Space Station flexibility

The first space station eigenmode of about 0.05 Hz requires at a first glance a lowering of the IPS bandwidth to less than 0.5 Hz. This is valid if the assumption can be made that the angular deflections due to the space station first eigenmode are negligable. An IPS performance similar to the IPS/Orbiter configuration may be achieved, a quick analysis has shown that the IPS can handle a larger but slower disturbance better, than it can handle a smaller but faster disturbance.

If the local angular deflections of the first eigenmode have to be compensated by the IPS, the controller bandwidth has to be increased to 2 to 4 Hz, lying then within the Space Station structural frequencies. So the lower structural frequencies have to be notched in the controller.

The controller structure will be different from the existing one. Modifications which can improve the situation include decoupling (e.g. magnetic bearing) and control by inertial systems (Reaction wheels, CMG).

Much more investigations have to be performed for stability assessments. The Space Station FEM has to be used for detailed analysis. Interaction is also expected with the payload model. An adaptive controller is recommended due to space station and payload changing characteristics. The feedforward loop (accelerometers) is recommended not to be used.

Operations

Task sharing is performed between CDMS and DCU. For the Space Station an additional processor is recommended, it has the following advantages

- required for adaptive controller
- increase autonomy
- increase flexibility

Safety

Reduced safety requirements are expected, because no reentry is planned (no cargo bay door closing constraints).

Power and Data

- the payload support power can be upgraded according to future payload requirements.

- the payload data lines are according to RAU, CDMS, STS capabilities.

Payload mass

- the IPS has been designed for payloads from 200 to 7000 kg, this seems to fit also with most of the space station candidate payloads.

Improvement for IPS

- better Gyros (noise, drift)

- separate Sun-Sensor

- wide FOV Acquisition Sensor

- on-board alignment calibration

  between IPS and space station inertial measurement unit reduces initial IPS AMA attitude error which relieves from the wide FOV acquisition sensor after first acquisition after launch

- additional control-loop based not on gyros, but on gimbal-resolvers for pointing relative to Space Station (e.g. during Space Station rotations or during IPS stowage/deployment or parking, back-up mode for loss of gyros) additional processor or RAM extension

- improvement of command-capability from the Experiment Computer (e.g. automatic sequencing)

- Improvement of bright star-triplet acquisition procedure ($\rightarrow$ SW) for bright stars search

- sun-sensor as fast attitude-sensor for fast loop control and not for attitude determination filter (ADF)

  ADF works only for roll-attitude and not for LOS in solar pointing

  different AMA-concepts for

  stellar
  solar pointing
  earth

- new/additional scan profiles

  o raster-point scan (stop-and-go)
  o sin/cos scan
  o etc.

- earth sensors in control-loop (landmark, horizon-sensors)

8.3.1.2 PHM

In general, the PHM is for hemispherical coverage for

- low to medium 2 axes pointing and stability requirements for

- small to medium sized payloads,

requiring from the Space Station in its non-autonomous operation mode the

- state vector of the Space Station to calculate a quasi-inertial attitude for inertial pointing or earth tracking.

Possible PHM users in the field of Astrophysics are smaller experiments running in parallel with advanced large astrophysical payloads who want to maintain independence and flexibility from those experiments.

Possible PHM users in the field of Environmental Observation are all kinds of antenna- or telescope-based experiments fitting the PHM capabilities.

The PHM can be upgraded without problems by use of dedicated sensors (Gyros, Optical Sensors). With the demonstration model a pointing accuracy of 0.5 arcmin was achieved with a Dornier off-the-shelf sun sensor.

No accommodation problems exist with payload power and data requirements.

The PHM controller bandwidth is nominally between 3 to 4 Hz. No interaction (as for the IPS) is expected between PHM and Space Station.

8.3.1.3 APM

Typical application would be in the fields of:

- the Space Stations own infrastructure such as TM/TC antennas for up-downlink purposes,
- antenna pointing for experiments with small, light weight antennas, and
- surveillance operations by supporting a (video) camera.

The APM can accommodate payloads with the performance and interface data as given in section 2.3.

8.3.2 Identification of Design Improvements

8.3.2.1 IPS

- Improvement of performance
    - o Adaptive/self optimizing control
    - o Modified controller/actuator concept
- Updated distributed microprocessor system

  - more flexibility, more autonomy, intelligence distribution

- Technology improvements

  - Sensor improvements, smart sensors (CCD/CID sensors etc.)
  - decoupling from Space Station or carrier e.g. magnetic bearings
  - cryo or fluidic connections to the payload

- Improvements with respect to maintenance/operations.

8.3.2.2 PHM

- Accommodation of payload dedicated sensors (inertial, sun, earth reference)

- Development of standardized interfaces (mech. and data)

- Use of dedicated processor

- Increase slew rates

8.3.2.3 APM

- Accommodation of larger antennas

- more powerful motors to increase slew rates

8.3.4 Pointing Systems Accommodations Summary

Most of the considered payloads of section 3 can be accommodated by IPS, PHM and APM. Additional investigations primarily have to be done with respect to:

IPS

- IPS/Space Station dynamics

  - definition of disturbances
  - set up a coupled Space Station/IPS finite element model

  - o analyze modified controller concepts
  - o perform simulations

- IPS Processor Accommodation

  - o S/W Requirements
  - o Task sharing between DCU, new processor and CDMS

- Analysis of future sensor developments

PHM

- Accommodation of payload dedicated sensors

- Development of standardized interfaces

APM

- Analyze accommodation of larger antennas

All three systems seem to be very well suited to be used as standard equipment for future Space Station missions.

9.0 THERMAL MANAGEMENT SUBSYSTEM

9.1 INTRODUCTION

The radiator concept, described in this technical section, is based on the requirements from Boeing and is part of the cooperation between Boeing and Dornier System within the 'Space Station Study'. This section contains a summary of the Dornier report which is included in full in Volume 7-4 Data Book.

The requirements mentioned are derived from the overall core module concept of the space station designed by Boeing. The radiator needs to be assembled in space, the individual radiator modules are stowed in up to 4 packages which are 1.75 m long by 0.5 m square. The modules will be attached to a central freon 21 loop system.

Main requirements:

- Q_{max} = 25 KW
- T_{Rad} = 323 K - 280 K
- Packages dimensions : 4 x 1.75 x 0.5 x 0.5 m
- No sun-shielding possible

The overall design consists of these radiator modules which possess the following main design features:

- Heat dissipation on the modules by means of heat pipes.
- Module size 1.7m x 0.5m.
- 2 Heat pipes per module.
- Radiation to both sides.

- o The heat pipes may be replaced by VCHP's (gas-stabilized heat pipes) for temperature control reasons.
- o Heat pipe and radiator sheet material is an aluminum alloy.

Problem areas:

- Heat pipe performance.
- Panel thickness and possibility to stow.
- High connecting area to central loop.
- Attachment mechanism of the panel modules.
- Low weight.
- Low cost and low development risk.
- Lifetime (10 years).

The design is based on the state of the art technique so that no development risk and minimized manufacturing and design costs exist.

9.2 MODULE DESIGN

Fig. 2.9-1 shows the radiator module and the heat pipe routing.

Figs. 2.9-2 and 2.9-3 show two possibilities for the heat pipe contact to the central loop.

Fig. 9-2 MODULE DESIGN

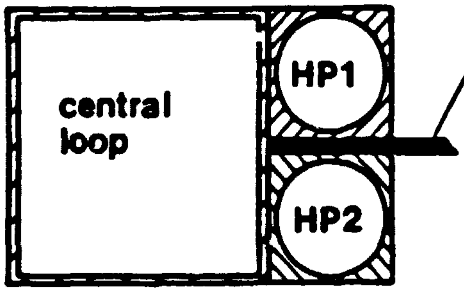

Figure 9-2

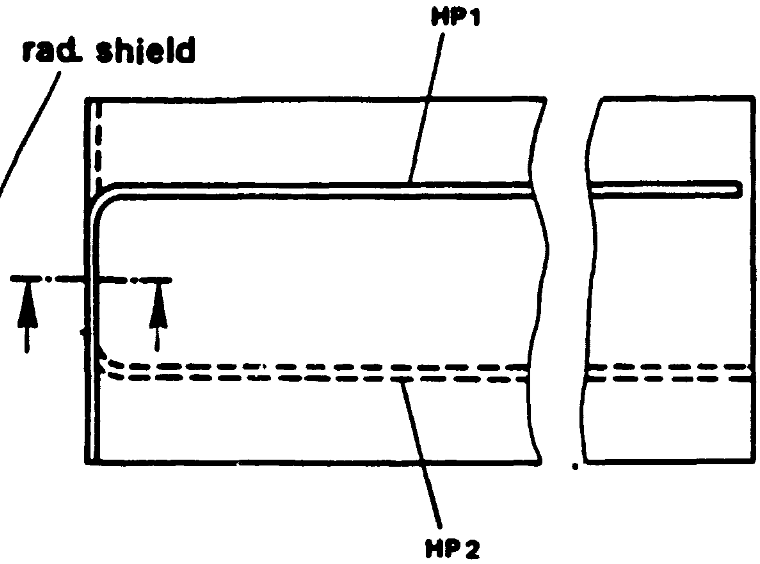

Figure 9-1

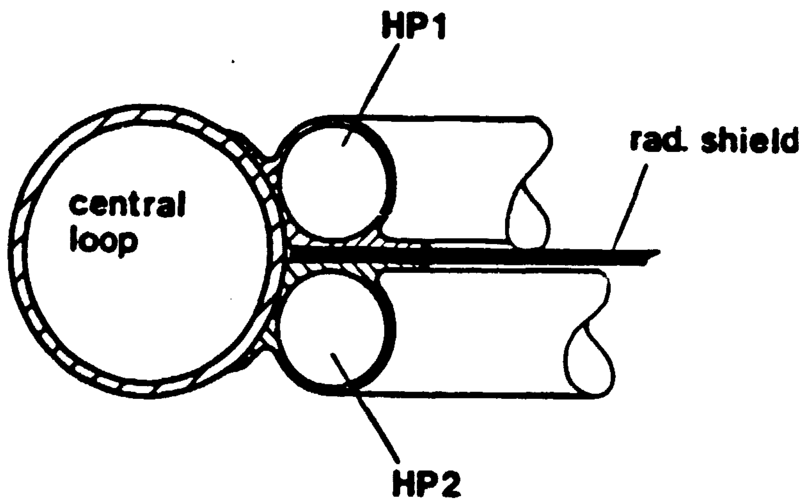

Figure 9-3

Fig. 9-1 shows the radiator module and the heat pipe routing.

Figs. 9-2 and 9-3 show two possibilities for the heat pipe contact to the central loop.

The heat pipes must possess a high contact area to the central freon- loop in order to minimize the temperature drop and the radial heat flux density. A long coupling area has therefore been designed. For weight reasons the radiator consists of a single aluminum plate, a honeycomb construction will not be necessary because of the stiffness of the heat pipe profiles which possess integrated fins (see Volume 7-4 for the profiles already available at Dornier). The heat pipes can be welded (on the fin) or bonded with an adhesive to the aluminum radiator plate.

9.3 LAY-OUT CALCULATIONS

The calculations are included in full in the Volume 7-4 Data Book.

9.4 OVERALL ARRANGEMENT OF THE RADIATOR

The radiation of one module without sun is about 600 Watt (average value) and about 425 Watt with full sun on one panel side (average value). Therefore a heat dissipation of 25 KW can be reached with a number of modules between 42 and 59. The arrangement can be done according to Fig. 2.9-4. The attachment of 60 modules (30 double modules) leads to an attachment length

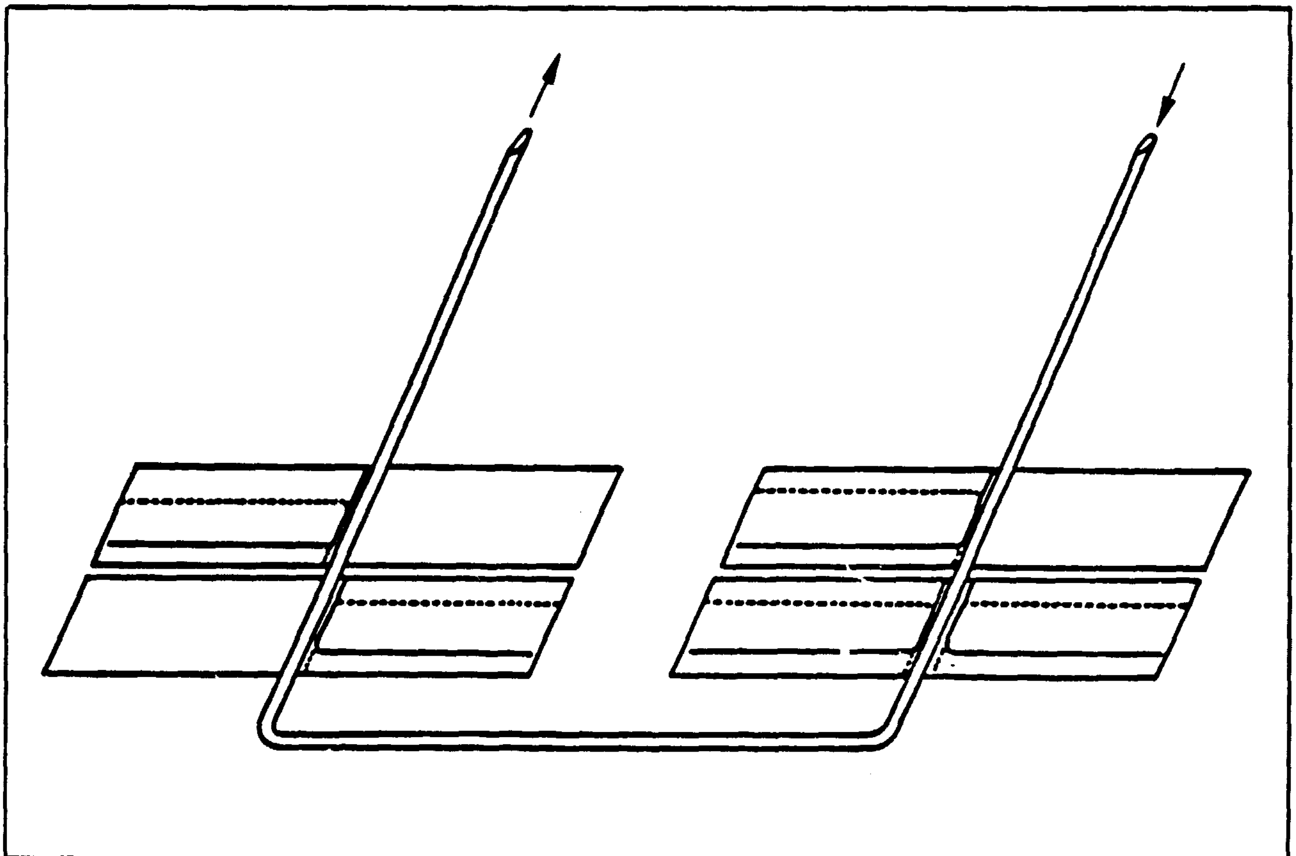

Figure 2.9-4

of 15 m if both sides of the loop are provided with these radiator modules. The total length of the central loop in the radiator area will be about 20 m.

9.5 RADIATOR PACKAGES

Before assembly the radiator modules have to be stowed in 4 packages with 1.75 x 0.5 x 0.5 m each. Because each module possesses an outer shape of 1.75 x 0.5 m, the modules may have a thickness of less than 3.3 cm (60 modules). A solution is sketched in Fig. 2.9-5. Here we reach about 20 modules per package or 80 modules in 4 packages.

9.6 REDUNDANCY ASPECTS

Each module possesses a certain redundancy because a failure of one heat pipe does not mean a failure of the entire module but a certain temperature drop of the module and therefore a reduced amount of radiation heat.

A failure of one module does not influence in any way another module. Nevertheless, some spare modules may be connected to the central loop for redundancy reasons.
Without any great effort in designing and manufacturing, such a radiator module may be provided with gas-stabilized heat pipes (VCHP) so that these modules serve not only for radiation but also for the temperature stabilization without any active electrical system such as a heater or controller.

The most critical part is the central cooling loop system itself (no redundancy) and possibly the attachment of the individual modules.

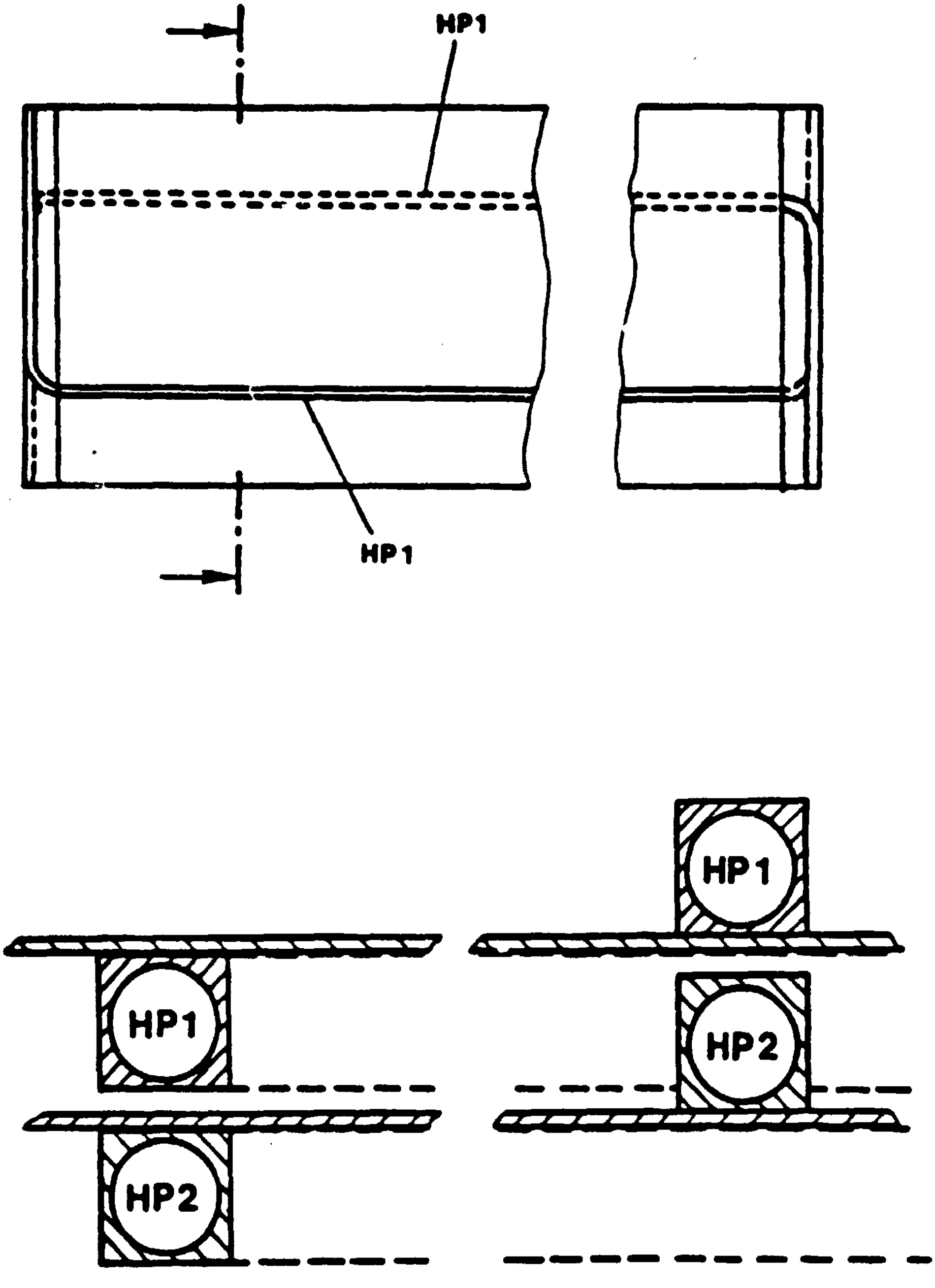

Figure 2.9-5

10.0 INTERFACE STANDARDIZATION

10.1 INTRODUCTION

The principal interfaces for the various classes of users, transportation vehicles, or facilities were examined. The objective of and analysis was to determine the interface services and configuration driver influences upon the Space Station system. The detailed report on this topic is found in Volume 7-4. This section summarizes the results.

10.2 SUMMARY

The principal conclusion was that there is an early need to define baseline interfaces in two principle areas.

1. Berthing/Docking Ports
2. Hangar Servicing/Maintenance/Checkout

10.2.1 Standardized Berthing/Docking Port

Emphasis should be placed on defining the physical requirements for a standardized berthing/docking port. The objective would be to conceptually design a standard berthing/docking port and derive the requirements for the following subsystem at this interface:

Structures/Mechanical
Docking/Berthing
Electrical Power
Thermal Control
ECLSS
Communications
Data Management

The conceptual designs should test the feasibility of developing a standardized fully maintainable interface that can meet the safety criteria involved.

10.2.2 Hangar Servicing/Maintainability/Checkout Interface

The hangar servicing/maintenance/checkout interface is a predominant factor in the arrangement architecture of the growth space station. It is important to the initial station configuration to know the growth restraints. It is recommended that this area of operation with OTV's, free flyers, and platforms be explored in enough detail to define the basic requirements and to estimate a realistic traffic model to derive the number of maintenance/service stations required. The objective would be to develop a greater understanding of the space stations architecture sensitivity to this important growth interface area.

3.0 TECHNOLOGY

The principal recommendations for high leverage technology advancement are presented in Figure 3-1. Subsystem technology recommendations were developed utilizing a matrix procedure in which technology selection interrelationships and principal mission orbit altitude and growth options were considered. The compl... m... rix appears in Figure 3-2.

High-Leverage Items

- **Integrated O_2-H_2 (... system for electrical energy storage and propulsion.**
- **Data Management - Packet-switching redundant networks, fiber optics. Use the best available state-of-the-art.**
- **EC/LSS water loop closure to minimize resupply requirements important for high-inclination missions.**
- **Communications Bandwidth - Provide for growth to millimeter -wave and laser com.**
  - **Set the "requirement" at what the state of the art can deliver - Don't let it be a cost driver.**
  - **Be wary of specifying digital color TV. State of the art questionable. Potential cost driver.**
- **Long life thermal coatings and alleviation of thermal coating degradation problems through use of thermal storage and steerable radiators.**
- **Automated housekeeping subsystems - Integration of automated electrical, thermal and ECLSS subsystems using expert system techniques.**

Figure 3-1. Technology

It has been popular in the past couple of years to consider incremental closing of the EC/LSS water and CO_2 loops. This is claimed to save money in early years when crews and hence resupply requirements may not be all that large. However, we recommend closing the water loop initially to minimize resupply requirements. This is very important for the high inclination missions where shuttle flights will be available infrequently and lift capability is small. A second reason for this recommendation is that if the engineering and integration required to close these loops is deferred until some hardware is in space, one may discover integration problems very difficult to solve by retrofit techniques. Consequently, we suggest that such deferrals of basic developmental and integration engineering create high technical and cost risks for the program. This consideration outweighs the relatively modest savings that might be

	MISSIONS	ORBIT ALTITUDE	GROWTH	STRUCTURES	ELECTRICAL POWER	PROPULSION	FLIGHT CONTROL & ATTITUDE CONTROL	COMMUNICATIONS	DATA MANAGEMENT	THERMAL CONTROL	EC/LSS	SUBSYSTEMS TECHNOLOGY RECOMMENDATION
MISSIONS					High power demand for some missions motivates their assignment to power platforms.	Can disturb zero-g environment, possible source of contamination & plume imp.	Accuracy will influence putting some missions on free-flyers. Space station target 5-°.	Bandwidth limits may influence selection of on-board processing.				
ORBIT ALTITUDE	Need 500 km Low-Incl to service Astrophysics Missions.	Selected maximum compatible with shuttle service: 500 km Low Inclination, 400 km High Inclination.			Drag motivates higher altitudes.							
GROWTH	Compatibility problems indicate 2 stations Low Incl to separate Operations & sciences.				Limits to practical station size presumably exist but not identified.	Plume impingement may limit growth avenues.	May impose limits to growth.					
STRUCTURES	Fire safety requires Metallic Cabin Interior, e.g. aluminum. Low outgassing required.		Structural precision needed to maintain standard dimensions so that future modules will fit.			Masts required for control authority	Will set stiffness requirements.			Structural Arrangements must observe view factor requirements.		. Aluminum pressure shells . GR-EP masts & external struct. . Evaluate metal-matrix . Determine collision characteristics of composites
ELECTRICAL POWER	Eventual power demand >100 kw. Put worst power demands on power platform.	Higher altitude lessens demand for high efficiency but still very valuable.	Must have a way to grow solar array to handle 75-100 kw load.	Shortening most design will result in occasional array shadowing. Array must accommodate.		Integrated O_2-H_2 system. See	More rigid solar arrays need investigation.	Load, but not a driver.		Integrated O_2-H_2 system easier to thermal control than batteries.	Consider power costs in selecting EC/LSS options.	. Solar arrays & integrated O_2-H_2 . Investigate flywheels . NiCd or NiH2 as backup
PROPULSION	Missions prefer low-thrust, low-contamination system.	Higher altitudes reduce thrust level requirements.	Power demand forecast dominates drag.		Integrated O_2-H_2 system is highly desirable (weights, safety, life, imp).		Attitude control propulsion needs masts for control authority & to minimize plume imp.			Integrated O_2-H_2 system easier to control than hydrazine or bi-prop.	Surpluses (CO_2 or methane) may match up with orbit makeup requirements.	. Integrated O_2-H_2 system . Evaluate Resisto jet with EC/LSS surpluses (looks promising) . Hydrazine as backup . Ion thrusters not attractive
FLIGHT CONTROL/ ATTITUDE CONTROL	Accurate pointing desirable. Target 5-° Both Earth and inertial pointing needed. CMG's	Higher altitude reduces drag torques.	Control authority needed.	First modes probably in 0.06 Hz range. Precision pointing may need sub-platforms Technology Advancement Areas.	Orientable solar arrays are the main cause of low structural frequency.	O_2-H_2 thrusters on masts provide backup to CMG's & add control authority.						CMG's with O_2-H_2 thruster backup . Grow into flexible mode control (software evolution) Inertial and Earth pointing.
COMMUNICATIONS	Some missions need high bandwidth. Laser & mm-wave systems need investigation.		Put in essential millimeter-wave equipment to take advantage of next-generation TDRSS	Some antennas are on masts. Cable runs and also need to be EVA serviceable.					Mission Data/ Communications interfaces need attention.			Present bands plus millimeter wave and laser Evaluate digital TV state-of-art carefully. May be cost driver
DATA MANAGEMENT	Missions need dedicated support with low software cost. Keep mission support software out of critical flight system computers		Requires Gram Network with packet switching, & distributed processing.		Expert systems housekeeping control desirable.		Expected to set computer throughput requirements for control of structural modes.	. Fiber optics for low EMI. . Onboard mission data processing.		Expert systems housekeeping control desirable.	Expert systems housekeeping control desirable	Distributed system . Base on standard hardware/software - not unique design. . Expert System housekeeping . Fiber Optics
THERMAL CONTROL	Thermal bus...ing essential because of high/vary'ng loads.		Each module needs to have thermal rejection capability approximately equal to its load	Module wrap-around radiators double as impact protection shields.	Source of most thermal loads	Check for plume impingement problems.					Cabin temperature & humidity control requirements set lower limit on thermal rejection temperatures.	High-capacity thermal busses . Module shell and fin radiators Cold-plated electronics . Long-life, restorable, or replaceable thermal coatings
EC/LSS	Need low contamination. High Incl. & high alt. ... low resupply/close water!	Could use CO_2 for orbit makeup.	Modular & incremental.		Co-ordination of cyclic loads with day-night cycle is beneficial.	May be desirable to use EC/LSS surpluses, e.g. CO_2. Could affect loop closure decisions						. Close water loop early . Don't defer systems eng'rg Evaluate open-loop LO_2, using CO_2 for orbit makeup

Figure 3-2. Subsystems Technology Selection Matrix Devision Factor

achieved by deferring water loop closure. One need not, of course, operate in the fully closed mode until the equipment and water purity are flight proven.

Additional technology issues are shown in Figure 3-3 and described below.

- **Stiffness and Flight Control**
  - **This issue needs further assessment. Pointing goal appears within reach.**
- **ET Scavenging**
  - **Appears feasible and desirable for space-based cryo OTV**
  - **Not attractive as an alternative to solar array power**
- **Autonomy and automation - High leverage on life cycle cost**
  Automation should be used to reduce crew workload and eliminate dependence on large cadre of ground mission controllers. Put the flight crew in charge (like an airplane crew).
- **Standardization - High leverage on life cycle cost**
  - **Use industry standard hardware and software wherever practical. Space qualify as necessary.**
  - **Unique/special designs require support of spares program over life of program.**

Figure 3-3. Other Technology Issues

Our space station configurations utilize Astro-mast deployable solar arrays on booms to place the solar array away from the immediate space station operational area and to reduce solar array shadowing for Earth oriented station operation. This leads to structural modes with frequencies less than 1/10 Hertz, and has raised concern that precision pointing of instruments from such a soft structure may be difficult or impossible. The issue needs further assessment, but at present the goal appears within reach. Further study and assessment are needed before one accepts space station configuration comprises simply to increase stiffness.

We continued to assess external tank scavenging. It appears to be feasible for propellant storage in an era when the orbit transfer vehicle is space based. However, it is not attractive as an alternative to solar array power. Using scavenged propellants with fuel cells would result in severe resupply requirements during a time when it is important to minimize space station demands on space transportation. It should be further noted that most earlier estimates of space station power requirements have been less than mission needs analysis indicated.

We believe that autonomy and automation, as well as standardization, have high leverages on initial and life-cycle cost for putting the flight crew in charge, reducing dependence on ground mission control and reducing crews workload. Additionally, a standardization program for hardware and software should be incorporated since unique and special designs will require separate qualification as well as the support of a spares program over the space station life.

4.0 PROGRAMMATICS

Cost Drivers Summary

Our cost estimates for space station were derived assuming conventional space practices, i.e. we used a history-based parametric cost model without imposing any special assumptions. There is, however, evidence that significant cost savings might be achieved relative to our nominal estimates. See Figure 4-1.

ITEM	IMPACT ON DDT&E	IMPACT ON INVESTMENT	IMPACT ON SPARE & SUPPORT	IMPACT ON OPERATIONS	COMMENTS
INADEQUATE DEFINITION; EXCESSIVE REQTS	? BUT HIGH	? BUT HIGH	? BUT HIGH	? BUT HIGH	SOME COMPARISON STUDIES HAVE SUGGESTED FACTOR OF 2 BUT NO REAL BASIS TO COMPARE
SPECS AND STANDARDS	100%	100%	MODERATE	LOW	
AUTONOMY	LOW TO MODERATE	LOW	MODERATE FAVORABLE	VERY HIGH FAVORABLE	FAILURE TO IMPLEMENT COULD NEGATE SPACE STATION BENEFITS
UNIQUENESS VS INDUSTRY STANDARD	10%	10%	FACTOR OF 2 TO 5	?	ISSUE IS NOT NEW VS OLD TECHNOLOGY
PAPER	30%	30%	?	?	
MAINTAINABILITY	10%	10%	LOW	HIGH TO EXTREME	FAILURE TO IMPLEMENT COULD NEGATE SPACE STATION BENEFITS

Figure 4-1. Cost Drivers Summary

Our estimates assumed adequate definition; that is, we did not include cost penalties for excessive change activity. We also assumed that requirements that stressed the available state of the art would not be accepted. Costing assumptions are shown in Figure 4-2.

Parametric cost models include environment or "platform" factors that slew the cost estimate. In the RCS PRICE model, "manned space" is the most costly environment of all. Other environments such as unmanned space or military aircraft are much less costly. This suggests that a careful review of specifications, standards and practices should be carried out to identify and eliminate those that are more costly than the benefit they provide.

Autonomy and maintainability will have such a large impact on life cycle cost that improper attention to either could negate space station economic benefits, which hinge on reasonable operational costs. Similarly, specification of a unique design where an industry standard could serve will have a severe impact on cost of maintaining a spares program. The issue is <u>not</u> new

1984 dollars

No schedule problems

Good definition

Normal specs and standards

Industry standard where practical

Normal paperwork

25% spares

2½ sets support equipment

Support equipment complexity factor 1.5

SE&I and ground test complexity factor 2.0

One prototype production unit used for integration testing

Figure 4-2. Costing Assumptions

versus old technology, but how widely spares production and sustaining engineering costs are shared.

In certain instances where technology advancement is highly desirable, the space station program may become the vehicle for creating a new industry standard. This is believed true in the cases of (1) Data management network architecture; (2) integrated O_2-H_2 systems; (3) EC/LS; (4) thermal control; and perhaps others.

Finally, we were exposed to one study that indicated thirty percent of the cost of a typical government program was in compilation of reports. The implication was that these were reports specified by contracts but not essential to accomplishment of the programs.

Cost Assumptions

The costing assumptions we used are summarized on the facing page.

System-Level Cost Relations

We updated all of our space station cost estimating data base to 1984 dollars and plotted the results as shown. This permitted the use of high-level curve fits to estimate the costs of modules such as airlocks that were not estimated in detail. These data include modules defined by the SOC study, Boeing IR&D, and the present space station study. Data are presented as defined in the parametric cost models, i.e. as DDT&E and unit costs. These relationships are presented in Figure 4-3.

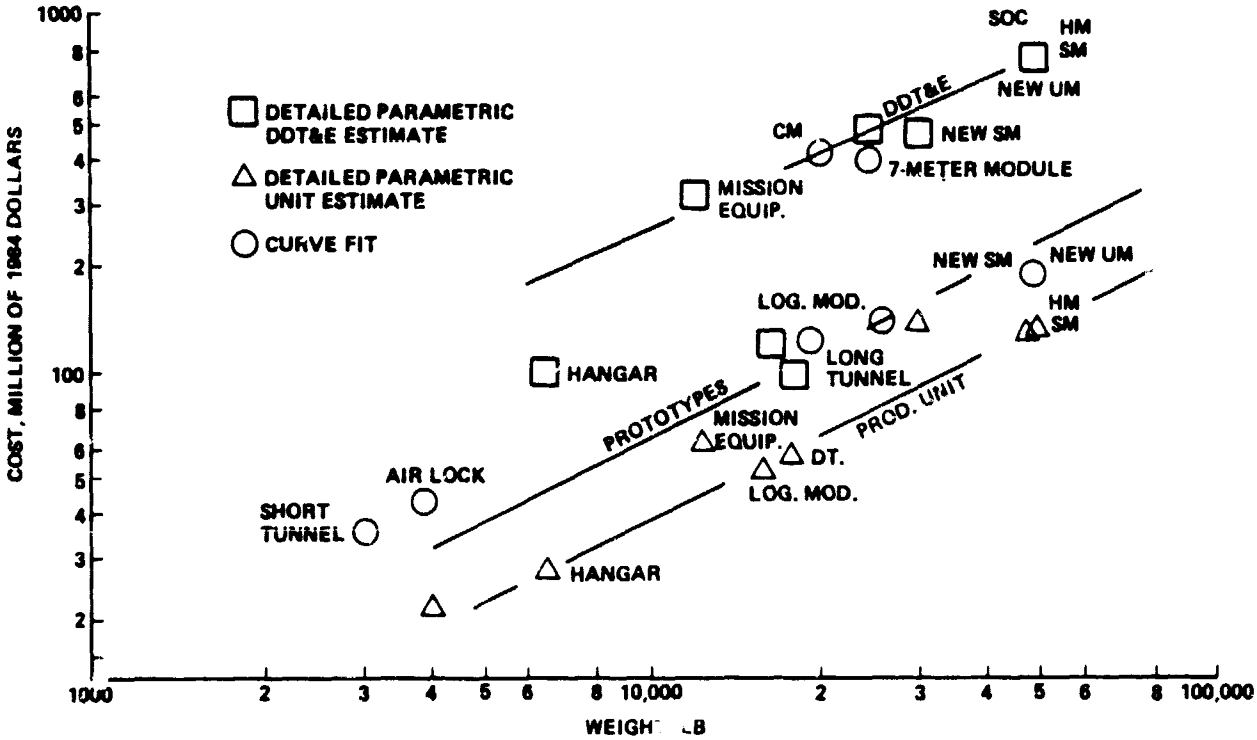

Figure 4-3. System-Level Cost Relationships

Cost Estimates Summary

Hardware acquisition and other costs are summarized in Figure 4-4. In this tabulation, manufacturing costs associated with DDT&E have been transferred to the DDT&E column. A nominal contractor fee of 10% has been added (most cost models estimate cost, not price). These include a test unit for each module and nonrecurring manufacturing costs such as tooling.

Additional DDT&E charges are shown for subsequent unit acquisition, recognizing that these will not be identical to prior units. The additional charges were roughly estimated as 25% of

HARDWARE ACQUISITION (INCLUDES FEE)						OTHER COSTS	
INCREMENTAL ARCHITECTURE			UNIFIED ARCHITECTURE				
ITEM	DDT&E*	INVEST.	ITEM	DDT&E	INVEST		
SERV. MOD.	720	165	UNIT MOD NO. 1	1250	220	SIL LAB(S)	60
C&C MODULE	670	130	UNIT MOD NO. N	315	220	PROGRAM-LEVEL INTEGRATION	10%–20%
AIR LOCK (2)	85	50	AIR LOCK (2)	85	50	FLIGHT SOFTWARE	100
7-METER NO. 1	710	165	LOGISTICS (2)	240	121	MISSION EQUIP SUITS, TOOLS, ETC	?
7-METER NO. N	180	165	HANGAR	165	35	SCIENCE, ETC.	?
SHORT TUNNEL	50	12	PROP STOR.	280	210	SUPPORT CONTRACTS	?
HANGAR	165	35	CONSTR EQUIP	350	165	TRAINING & SIMUL	?
PROP STOR.	280	210				SHUTTLE FLIGHTS	71
CONSTR EQUIP.	350	165				CIVIL SERVICE	?
						CONTINGENCIES	30%

*INCLUDES TEST HARDWARE & NONRECURRING MANUFACTURING

Figure 4-4. Cost Estimates Summary (Values in Millions of 1984 Dollars)

the initial DDT&E. A variety of "other" costs must be included in a complete program estimate. Some of these can be only roughly estimated at the present time.

Initial Costs of Alternative Program Scenarios

Initial costs of four architecture/program scenario options were estimated as summarized in Figure 4-5. "Other" costs were included, as were considerations of numbers of hardware units required.

The "bare bones" program provides a permanent manned presence in space, but little else. The space station utilizes the incremental architecture without dedicated habitat or lab modules. It represents the minimum feasible space station program.

The program-constrained architecture paces space station buildup based on projected space station funding availability rather than onset of mission needs as projected by the mission needs analysis. The initial cost of this program is within the range of the NASA-published estimates of four to six billion dollars.

The mission-driven program establishes stations in both low and high inclination orbits by 1992. It substantially exceeds the nominal NASA estimate.

	INCREMENTAL ARCHITECTURE				UNIFIED ARCHITECTURE*
	BARE BONES PROGRAM (LOW INCL)	PROGRAM CONSTRAINED (LOW INCL)	MISSION DRIVEN		MISSION DRIVEN (LOW INCL)
			LOW INCL	HIGH INCL	
SERVICE MODULE	890	890	890	165	0
COMMAND MODULE	800	800	800	130	0
7-METER MODULES	0	1220	1220	345	2540 (3 UNITARY)
AIRLOCKS	135	135	135	100	135
TUNNEL	0	62	74	0	0
LOGISTICS MODULES	360	360	360	120	360
SIL LABS	60	60	60	20	50
FLIGHT SOFTWARE	50	100	100	50	100
LABS	0	0	690	0	0
MISSION EQUIPMENT	100	200	300	100	300
OTHER	100	200	200	100	200
SHUTTLE FLIGHTS	140	285	425	285	355
PROGRAM INTEGRATION	265	650	790	210	610
TOTAL	2900	4962	6044	1625	4650

*DOESN'T SUPPORT HIGH INCLINATION OPERATIONS

Figure 4-5. Initial Costs of Alternative Program Scenarios (1984 Dollars)

Using the unified architecture and ignoring the high-inclination mission needs, a space station that serves the rapid onset of low-inclination missions can probably be acquired for less than six billion dollars.

If some of the cost saving potentials discussed above could be realized, even the highest-cost mission-driven scenario could probably be afforded.

Program Strategy

The key points of our recommended program strategy are tabulated in Figure 4-6. A breakdown of subsystems is shown in Figure 4-1.

- Examine high-inclination mission requirements, costs, and benefits and select architectural options for necessary flexibility.

- Structure program so that commercial and foreign users pay their own way as early as possible, i.e., investment phase.

- Select technologies compatible with potential DoD applications.

- Emphasize life cycle cost in all decisions.

- Zero-base requirements and specifications selection.

Figure 4-6. Program Strategy

APPENDIX 1

SUMMARY OF STUDY TASKS AND FINAL REPORT TOPICAL CROSS REFERENCE

SUMMARY OF STUDY TASKS

The study accomplished 3 major objectives:

1. Identified, collected, and analyzed science, applications, commercial, national security, technology development and space operations missions that require or benefit by the availability of a permanently manned space station. The space station attributes and characteristics that will be necessary to satisfy these requirements were identified.
2. Identified alternative space station architectural concepts that would satisfy the user mission requirements.
3. Performed programmatic analyses to define cost and schedule implications of the various architectural options.

Figure A-1 shows the summary task flow that was used to accomplish these objectives.

In Tasks 1.1 thru 1.5, missions were identified, screened, and their needs and benefits analyzed. Mission investigators were assigned to each of the mission classes (science and applications, commercial, technology development, space operations, and national security). In general, these investigators (and their supporting subcontractors) contacted potential users and analyzed available data to characterize potential mission needs. They worked in conjunction with designers and operations analysts to characterize the potential payloads and operational interfaces. In Task 1.6, the missions were allocated to orbits, and were assigned to platforms, free-flyers, or space stations, as appropriate. During Task 1.7, the various missions were integrated into time-phased mission models. The time-phasing took into account available budgetary constraints, prioritization, time sequencing constraints, and transportation availability. A computer program was used to process the integrated time-phased mission model to derive a year-by-year shuttle manifest schedule. The computer program was also used for Task 1.8 to derive the integrated time-phased space station accommodation requirements, i.e., power and thermal demands, berthing requirements, and crew skills. These mission analyses have been reported in Volume 2 of the final report.

Also included in Volume 2 are the results from Task 1.10. In this task, some of the primary commerical opportunities were examined to define the economics of the use of a space station and to define the benefits of doing business on a space station relative to doing it using the shuttle.

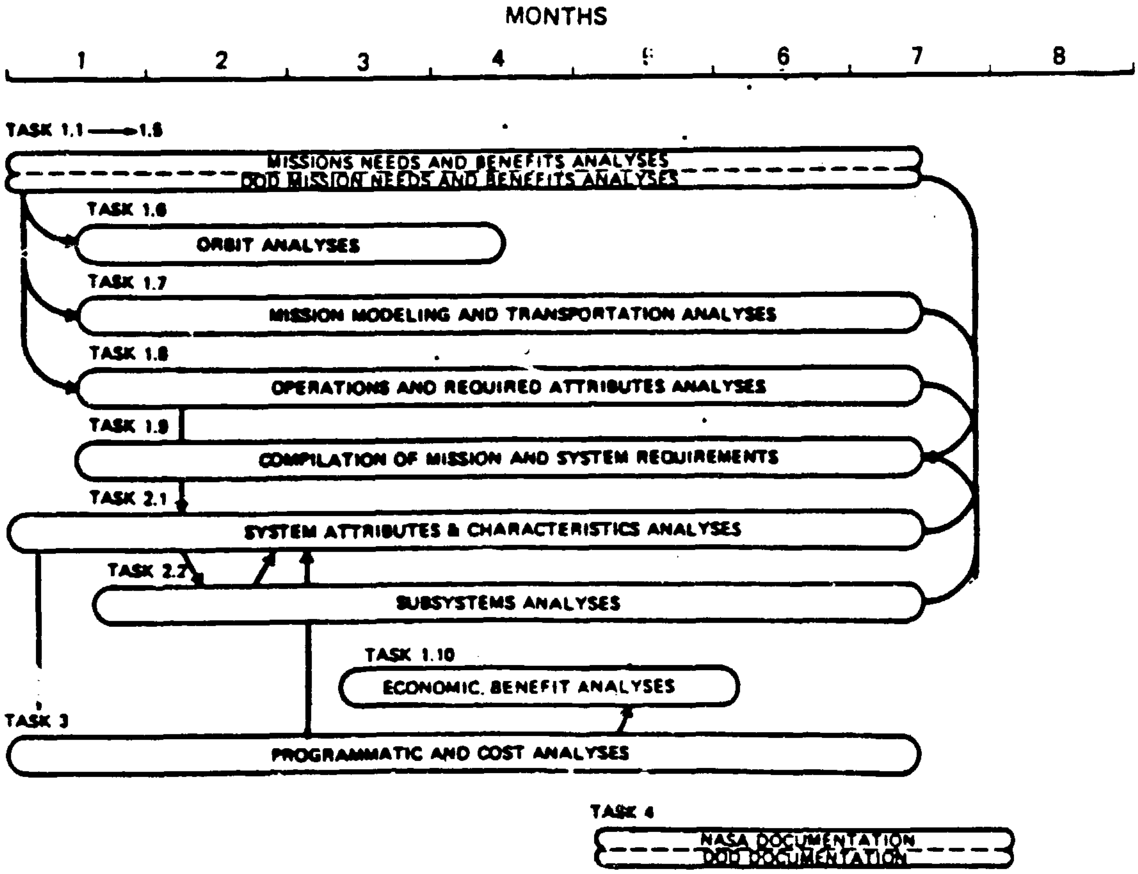

Figure A-1. Summary Diagram Outlines Major Task Traffic

In Task 1.9, mission requirements and space station design requirements were identified. An aggregate of these requirements are reported in Volume 3.

Volume 4 of the final report contains the results from Tasks 2.1, 2.2 and 3. Specifically in Task 2.1, a methodology for defining realistic architectural options was established. This methodology was applied using the requirements defined in the previous tasks. From this, we have created 3 architectural options and have shown some reference space station configuration concepts for each architectural option. Task 2.2 was performed to obtain analysis and trades of some of the principle subsystems, i.e., data management, environmental control and life support, and habitability. Task 3 provides the analyses of programmatics and cost options associated with the concepts derived during the study.

A cross reference guide to enable locating study topics within the volumes and volume sections of the final report is presented in Table A-1.

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Commercial Missions											
o Communication Satellites	o	3.2.1				o		o			
o Reconfigurable o Multibeam											
o Materials Proc.	o	3.2.2		I-1.3.2.3, 1.2.2.1		o		o			
o Semiconductors o Biological o Glass Fibers											
o Earth Observation		3.2.3									
Industrial Services		3.2.4						o			
o Crew Selection & Training o In-Space OPS											
Technology Demo's	o	3.3				o			o		
Space Operation	o	3.4				o					
o Construction o Flight Support o Servicing											

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TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Science & Applications Missions											
o Space Environment Missions	o	3.1.2				o	o				
o Astrophysics Missions	o	3.1.3				o	o				
o Earth Environment Missions	o	3.1.4				o	o				
o Life Sciences Missions	o	3.1.5				o	o				
o Materials Science Missions	o	3.1.6					o				
Scenarios of Operational Capabilities o Mission Constrained o Station Constrained o No Space Station	o	4.0, 5.0				o					

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Mission Requirements Summary		5.0									o
o Low Inclination Space Station	o	5.2,5.3	3.2.1	I-1.2.2.4		o					o
o High Inclination Space Station	o	5.2,5.3		I-1.2.2.4		o					o
o Platform only	o	5.4				o					o
o Manifesting o Shuttle o OTV o TMS	o	5.2, 5.3, 5.4				o					
o Crew Size	o	5.2,5.3 5.4	3.2.1			o					o
o Crew Skills		5.2.5.3 3.1.2.5, 3.1.3.5, 3.1.4.5, 3.1.5.5, 3.2.1.5, 3.2.2.6, 3.2.3 3.3		II-2.2.3							o

TABLE A-1

Final Report Topical Cross Reference Guide

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Mission Requirements Summary (Continued)											
o Accommodations Reqm'ts	o	2.2 5.2,5.3	3.2.1			o					o
o Power		5.4	I-1.2.1.2, 1.2.2.4 1.2.3.3 1.2.3.4								
o Internal Vol											
o Berthing Ports											
Benefits		6.0									
o Semiconductor Manufacturing	o	6.2				o					o
o Glass Fiber Manufacturing	o	6.3				o					o
o Communications Satellite Assembly	o	6.4				o					o
o Biological Materials Manufacturing	o	6.5				o					o

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Mission Analysis											
o Manifesting Analysis Software	o	2.2				o					o
o Accommodations & Crew Activity Analysis Software o Crew Skills o Crew Size o Berthing Ports o Electrical power o Internal volume	o	2.2				o					o
Design Requirements											
o Mission Accommodation Reqm'ts		5.0	3.2								
o Interfaces				II-10.0						o	
o Berthing/Docking Port				I-1.3.2.1							
o Hangar		3.3		I-1.3.2.2							

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Architectural Options											
o Architecture Development Methodology	o			I-1.1		o				o	
o Space Station Architectural Options	o			I-1.2		o				o	
Build-up and Growth	o	5.0		I-1.2.3.4, 1.3.1.3, 1.3.2.3, 1.3.3.3							
Data Management											
o Architecture				II-3.2						o	
o In-Flt Checkout				II-3.3						o	
o Space-Ground Integration				II-3.4						o	
o Ground Lab				II-3.5						o	
o Software Devel.				II-3.6						o	
o Hardware Stds				II-3.7						o	
o Software Stds				II-3.8						o	
o Verif/Valid.				II-3.9						o	

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Logistics/Resupply											
o Logistics Module				II-7.1, 7.3,7.4							
o Resupply Reqm'ts				II-7.2							
Environmental Control and Life Support Subsystem				II-5.0						o	
o ECLS Evolution				II-5.2.1, 5.3.2						o	
o Safe Haven Logistics Module				II-5.2.1						o	
o Air Revitalization System				II-5.0,5.3.2						o	
o Water Revitalization System				II-5.0,5.3.2						o	
o Performance and Loads Specification										o	
o Overboard Venting				II-5.2.1,5.2.2						o	
o Architecture				II-5.2.1						o	
o Water Recovery System				II-5.0,5.3.2						o	
o CO_2 Concentration				II-5.0,5.3.2						o	
o Regenerative-Fuel-Cell-Based ECLS				II-5.0,5.2.1, 5.3.2						o	
o Recommendations				II-5.0, 5.3.2						o	
EVA/EMU				II-5.0, 5.2.2						o	

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Communications & Tracking Subsystem			3.2.2.1.11	II-4.0						o	
Manipulator System				II-6.0						o	
Pointing Systems				II-8.0						o	
Thermal Management				II-9.0						o	
Crew				II-2.0							
o Tasks				II-2.2						o	
o Skills		5.2.5.3 3.1.2.5, 3.1.3.5, 3.1.4.5, 3.1.5.5, 3.2.1.5 3.2.2.6, 3.2.3 3.3		II-2.2.3							
o Capabilities				II-2.2.2						o	
o Role Relationships				II-2.3.2						o	
o Accommodations			3.2.2.1.11	II-2.4						o	

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Crew (Continued)											
o Habitability	o		3.2.2.1.11	II-2.0,2.4						o	
o IVA Work Stations				II-2.5.2						o	
o EVA Work Stations				II-2.5.3 II-5.2.2						o	
o Maintenance				II-2.5.4						o	
o Stowage			3.2.2.1.11							o	
o Windows			3.2.2.1.11	II-2.4.1						o	
o Hygiene			3.2.2.1.11	II-2.4.2.4						o	
o Scheduling			3.2.2.1.11	II-2.3.1						o	

APPENDIX 2

KEY TEAM MEMBERS

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Subject	Boeing Team	Subcontractor Team	
Study Manager	Gordon Woodcock	ADL:	Dr. Peter Glaser
		Battelle:	Kenneth E. Hughes
		ECON:	John Skratt
		ERIM:	Albert Sellman
		Hamilton Standard:	Harlan Brose
		Intermetrics:	John Hanaway
		Life Systems:	Franz Shubert
		MRA:	Col. Richard Randolph (Ret.)
		NBS:	Dr. B. J. Bluth
		RCA:	Dr. Herbert Gurk
		SAI:	Dr. Hugh R. Anderson
Technology Manager	Dr. Richard L. Olson		
Mission Analysis			
Science & Applications	Dr. Harold Liemohn	SAI:	Dr. Hugh R. Anderson (Environmental Science)
	David Tingey (Earth Obs.)		
	Dr. Derek Mahaffey (Mission Integration)		Dr. Peter Hendricks (Meterology/ Oceanography)
	Melvin W. Oleson (Life Sciences)		Dr. Gil Stegen
	Dr. Robert Spiger (Plasma physics, astro-physics, solar physics)		Dr. John Wilson (Life Sciences)
			Dr. Robert Loveless (Integration)
			Dr. Robin Muench
			Dr. Stuart Gorney (Life Sciences)
			Ms. Monica Dussman (Life Sciences)
		ERIM:	Albert Sellman (Earth Obs.)
			Dr. Irvin Sattinger (Earth Obs.)
Commercial	Dr. Harvey Willenberg	RCA:	Dr. Herbert Gurk
			Thaddeus (Ted) Hawkes
		ADL:	Dr. Peter Glaser
		Battelle:	Dr. Kenneth E. Hughes
		MRA:	Col. Richard Randolph (Ret.)
			Robert Pace

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Technology Demonstrations	George Reid Dr. Alan G. Osgood David S. Parkman Steve Robinson Richard Gates Tim Vinopal		
National Defense	Robert S.Y. Yoseph	ERIM:	Mirko Najman
Space Operations	Keith H. Miller		
Architecture and Subsystems			
Architecture & Configurations	John J. Olson Brand Griffin Tim Vinopal David S. Parkman Steve Robinson		
Communications		RCA:	Donald McGiffney
Crew Systems	Keith H. Miller George Reid Dr. Alan G. Osgood	NBS:	Dr. B. J. Bluth
Data Management and Software	Les Holgerson	Intermetrics:	John Hanaway
ECLSS	Keith H. Miller	Ham Std:	Harlan Brose Ross Cushman Al Boehm Ken King Todd Lewis
		Life Systems:	Dr. R. A. Winveen Franz Schubert Dr. Dennis B. Heppner
Operations Analysis	Keith H. Miller George Reid Dr. Alan G. Osgood		
Orbit Analysis	Dani Eder		

KEY TEAM MEMBERS (Cont'd)

Subject	Boeing Team	Subcontractor Team	
Architecture and Subsystems (Cont'd)			
Orbit/Survivability Analysis	Stephen W. Paris Merri Anne Stowe		
C^3I	H. Paul Janes		
Radiation Effects	Dr. William C. Bowman		
Requirements Analysis	Lowell Wiley		
Programmatics & Cost			
Cost Analysis	Ken verGowe	ECON:	Ed Dupnick
Programmatics	Gordon Woodcock		

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Programmatics & Cost			
Cost Analysis	Ken verGowe	ECON:	Ed Dupnick
Programmatics	Gordon Woodcock		

LIST OF ACRONYMS AND ABBREVIATIONS

AAP	Airlock Adapter Plate
AC	Alternating Current
ADM	Adaptive Delta Modulation
AM	Airlock Module
APC	Adaptive Predictive Coders
APSM	Automated Power Systems Management
ACS	Attitude Control System
ARS	Air Revitalization System
ASE	Airborn Support Equipment
BIT	Built in Test
BITE	Built in Test Equipment
CAMS	Continuous Atmosphere Monitoring System
C&D	Controls and Displays
C&W	Caution and Warning
CCA	Communications Carrier Assembly
CCC	Contaminant Control Cartridge
CCTV	Closed Circuit Television
CEI	Critical End Item
CER	Cost Estimating Relationship
CF	Construction Facility
CMG	Control Moment Gyro
CMD	Command
CMDS	Commands
CO_2	Carbon Dioxide
CPU	Computer Processor Units
CRT	Cathode Ray Tube
dB	Decibels
DC	Direct Current
DCM	Display and Control Module
DDT&E	Design, Development, Test, and Evaluation
DOD, DoD	Department of Defense
DT	Docking Tunnel
DM	Docking Module
DMS	Data Management System
DSCS	Defense Satellite Communications System
ECLSS	Environmental Control/Life Support System
EDC	Electrochemical Depolarized CO_2 Concentrator
EEH	EMU Electrical Harness
EIRP	Effective Isotropic Radiated Power
EMI	Electromagnetic Interference
EMU	Extravehicular Mobility Unit
EPS	Electrical Power System
ET	External Tank
EVA	Extravehicular Activity
EVC	EVA Communications System
EVVA	EVA Visor Assembly
FM	Flow Meter
FMEA	Failure Mode and Effects Analysis
ftc	Foot candles
FSF	Flight Support Facility
FSS	Fluid Storage System
GaAs	Gallium Acsenide

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

GN&C	Guidance, Navigation and Control
GEO	Geosynchronous Earth Orbit
GHZ	Gigahertz
GPC	General Payload Computer
GPS	Global Positioning System
GSE	Ground Support Equipment
GSTDN	Ground Satellite Tracking and Data Network
GFE	Government Furnished Equipment
GTV	Ground Test Vehicle
HLL	High Level Language
HLLV	Heavy Lift Launch Vehicle
HM	Habitat Module
HMF	Health Maintenance Facility
HPA	Handling and Positioning Aide
HUT	Hard Upper Torso
Hz	Hertz (cycles per second)
ICD	Interface Control Document
IDB	Insert Drink Bag
IOC	Initial Operating Capability
IR	Infrared
IVA	Intravehicular Activity
JSC	Johnson Space Center
KBPS	Kilo Bits Per Second
KM, Km	Kilometers
KSC	Kennedy Space Center
lbm	Pounds Mass
LCD	Liquid Crystal Display
LCVG	Liquid Cooling and Ventilation Garment
LED	Light Emitting Diode
LEO	Low Earth Orbit
LiOH	Lithium Hydroxide
LM	Logistics Module
LPC	Linear Predictive Coders
LRU	Lowest Replaceable Unit
LSS	Life Support System
LTA	Lower Torso Assembly
LV	Launch Vehicle
lx	Lumens
MBA	Multibeam Antenna
mbps	Megabits per second
MHz	Megahertz
MMU	Manned Maneuvering Unit
MM-Wave	Millimeter wave
MOTV	Manned Orbit Transfer Vehicle
MRWS	Manned Remote Work Station
MSFN	Manned Space Flight Network
N/A	Not Applicable
NBS	National Bureau of Standards
NSA	National Security Agency
N	Newton
NiCd	Nickel Cadmium
NiH_2	Nickle Hydrogen

APPENDIX 3

ACRONYMS AND ABBREVIATIONS

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

Nm,nm	Nautical miles
N/m^2	Newtons per meter squared
OBS	Operational Bioinstrumentation System
OCS	Onboard Checkout System
OCP	Open Cherrypicker
OMS	Orbital Manuevering System
OTV	Orbital Transfer Vehicle
PCM	Pulse Code Modulation
PCM	Parametric Cost Model
PEP	Power Extension Package
PIDA	Payload Installation and Deployment Apparatus
P/L	Payload
PLSS	Portable Life Support System
PM	Power Module
POM	Proximity Operations Module
ppm	Parts per Million
PRS	Personnel Rescue System
PSID	Pounds per Square Inch Differential
RCS	Reaction Control System
REM	Roentgen Equivalent Man
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Remote Manipulator System
RPM	Revolutions Per Minute
RPS	Real-time Photogrammetric System
SAF	Systems Assembly Facility
SAWD	Solid Amine Water Desorbed
SPGaAs	Space Produced Gallium Arsenide
scfm	Standard Cubic Feet per Minute
SCS	Stability and Control System
SCU	Service and Cooling Umbilical
SDV	Shuttle - Derived Vehicle
SDHLV	Shuttle - Derived Heavy Lift Vehicle
SEPS	Solar Electric Propulsion System
SF	Storage Facility
SM	Service Module
SOC	Space Operations Center
SOP	Secondary Oxygen Pack
SRB	Solid Rocket Booster
SRMS	Shuttle Remote Manipulative System
SRU	Shop Replacable Units
SSA	Space Suite Assembly
SSME	Space Shuttle Main Engine
STS	Space Transportation System
SSP	Space Station Prototype
STAR	Shuttle Turnaround Analysis Report
STDN	Spaceflight Tracking and Data Network
STE	Standard Test Equipment
TBD	To Be Determined
TDRSS	Tracing and Data Relay Satellite System
TFU	Theoretical First Unit
TGA	Trace Gas Analyzer

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

TIMES	Thermoelectric Integrated Membrane Evaporation System
TLM	Telemetry
TM	Telemetry
TMS	Teleoperator Maneuvering System
TT	Turntable/Tilttable
TV	Television
UCD	Urine Collection Device
VCD	Vapor Compression Distillation
VDC	Volts Direct Current
VLSI	Very Large Sacle Integrated Circuits
VSS	Versatile Servicing Stage
WBS	Work Breakdown Structure
WMS	Waste Management System